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Thermal Response and Reusability Testing of Advanced Flexible Reusable Surface Insulation and Ceramic RSI Samples at Surface Temperatures to 1,200°F

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ARO, Inc.

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ARNOLD ENGINEERING DEVELOPMENT CENTER
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Ten-minute exposure tests were performed on samples of an advanced flexible reusable surface insulation (AFRSI) made of a quartz glass fabric and samples of a ceramic tile reusable surface insulation (RSI). The samples were tested in a wind tunnel aerothermal environment that caused the sample surface to heat to 1,200°F during each exposure. No serious defects in the samples were detected as a result of the exposure. The test

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technique used provided a suitable aerodynamic heating environment for candidate materials evaluation.

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PREFACE

The work reported herein was conducted by the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), at the request of the National Aeronautics and Space Administration (NASA), Johnson Space Center (JSC), Houston, Texas, for the NASA/Ames Research Center (ARC), Mountain View, California. The results of the test were obtained by ARO, Inc., AEDC Group (a Sverdrup Corporation Company), operating contractor for the AEDC, AFSC, Arnold Air Force Station, Tennessee, under ARO Project Number V41C-56. The NASA-JSC program manager was Mr. Bill Moseley (E53), and the NASA-ARC program managers were Messrs. Howard Goldstein and Roy Wakefield. The data analysis was completed on June 28, 1979, and the manuscript was submitted for publication on August 2, 1979.

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1.0 INTRODUCTION

The structure of the space shuttle orbiter will be protected from the reentry thermal environment by a system of ceramic Reusable Surface Insulation (RSI) tiles that can be replaced quickly, as necessary, after one or several missions. This thermal protection system design allows quick turn around of an orbiter subsequent to a mission and thereby makes the shuttle concept cost effective; however, the cost of this system is significant. In an effort to reduce the total insulation costs, the National Aeronautics and Space Administration/Ames Research Center (NASA/ARC) has developed a less expensive Advanced Flexible Reusable Surface Insulation (AFRSI) for possible use on the leeward surfaces of the orbiter as a replacement for the ceramic tiles. The AFRSI will experience relatively low heating rates and is expected to reach an equilibrium surface temperature of about 1,200°F.

The suitability of the AFRSI requires testing in a simulated environment prior to commitment for use on the orbiter. Radiant heating facilities provide the required temperature but not the other necessary conditions, most notably the surface shear. Plasma jet facilities provide the desired temperature and shear, but the shear and heating rates are often too high. Moreover, particles in the flow for these facilities can produce serious material erosion, distorting the performance evaluation. The AFRSI needs to be tested in a clean, convective heating environment that provides realistic surface shear. The AEDC von Kármán Gas Dynamics Facility (VKF) Hypersonic Wind Tunnel (C) satisfies these requirements and was selected for testing the AFRSI samples largely because several materials evaluation tests have been conducted in this facility over the years. A summary description of the testing techniques developed from these tests is presented in Ref. 1.

In the present application the desired test environment was obtained by utilizing a wedge to support the materials samples and inclining it at a 25-deg angle to the Tunnel C Mach number 10 flow. The desired surface temperature and shear values, which were the primary test conditions, were provided.

The principal objectives of the subject test were to determine the thermal response and reusability of the AFRSI thermal protection materials. A second objective was to obtain performance comparisons between AFRSI materials and the ceramic RSI tiles which the AFRSI are intended to replace. This report presents a description of the test technique utilized and some typical test results.

2.0 APPARATUS

2.1 TEST FACILITY

Tunnel C (Fig. 1) is a closed-circuit, hypersonic wind tunnel with a Mach number 10 axisymmetric contoured nozzle and a 50-in.-diam test section. The tunnel can be operated continuously over a range of pressure levels from 200 to 2,000 psia with air supplied by the VKF main compressor plant. Stagnation temperatures sufficient to avoid air liquefaction in the test section (up to 1,800°F) are obtained through the use of a natural gas-fired combustion heater in series with an electric resistance heater. The entire tunnel (throat, nozzle, test section, and diffuser) is cooled by integral, external water jackets. The tunnel is equipped with a model injection system, which allows removal of the model from the test section while the tunnel remains in operation. A description of the tunnel may be found in the *Test Facilities Handbook* (Ref. 2).

The local flow conditions needed to meet the test requirements were produced by using a large wedge to process the tunnel free-stream Mach number 10 flow through an oblique shock wave. Varying the wedge angle and the tunnel free-stream conditions tailored the flow conditions on the surface of the wedge (where the material samples were placed) to provide the needed local flow conditions. The wedge (Fig. 2) is a 15-in.-wide by 41.5-in.-long flat plate mounted on a 13-deg wedge block. The flat plate has a 1.5-in. backstep occurring 17.5 in. aft of the sharp leading edge, which permits mounting material samples flush with the plate surface. It was desired that a turbulent boundary layer exist on the material samples. This was accomplished by welding three rows of 0.078-in.-diam spheres across the wedge, 3 in. from the leading edge. These spheres caused the normally laminar boundary layer to transition to turbulent flow. An installation sketch of the spheres is also shown in Fig. 2.

2.2 TEST ARTICLE

Four test articles were furnished by NASA/ARC, photographs of which are presented in Fig. 3. These articles, or samples, were fabricated at NASA/ARC and consisted of various combinations of Advanced Flexible Reusable Surface Insulation (AFRCI) and ceramic Reusable Surface Insulation (RSI). Shown in Fig. 4 are planform sketches of the test articles denoting the different combinations of insulation used on each sample. Using several materials on the same test sample enabled direct comparisons of the thermal response of these materials. In addition, the total wind tunnel test time required to test the various materials was reduced. Variations among the AFRSI samples were the weight of the fabric, the weave of the quilting, the felt thickness, and the edge formation. The RSI samples were of different thicknesses and had various silicon coatings applied to their surfaces. Typical

construction characteristics for the AFRSI and RSI tiles are also shown in Fig. 4e. All samples were bonded to 1/8-in.-thick aluminum plates which in turn were attached to Bakelite® plates of various thicknesses to maintain a total thickness of 1.50 in.

2.3 TEST INSTRUMENTATION

2.3.1 Tunnel Conditions

Tunnel C stilling chamber pressure is measured with a 500- or 2,500-psid transducer referenced to a near vacuum. Based on periodic comparisons with secondary standards, the accuracy (a bandwidth which includes 95 percent of the residuals, i.e., 2σ deviation) of the transducers is estimated to be within ±0.16 percent of pressure or ±0.5 psi, whichever is greater, for the 500-psid range and within ±0.16 percent of pressure or ±2.0 psi, whichever is greater, for the 2,500-psid range. Stilling chamber temperature measurements are made with Chromel® -Alumel® thermocouples which have an uncertainty of ±(1.5°F + 0.375 percent of reading in °F).

2.3.2 Test Data

The instrumentation in each sample consisted of thermocouples (22 in samples 1, 3, and 4; 23 in sample 2) placed at positions of interest to evaluate the thermal response. The thermocouples were of AWG No. 36 (0.005-in. diam) platinum/platinum-rhodium (13 percent) material. The locations of these thermocouples in the samples are shown in Fig. 5. The precision of these thermocouple measurements is ±4 deg for temperatures between 70 and 1,200°F.

A radiometer supplied by NASA/ARC was utilized to view a 0.5-in.-diam area of the sample surface about 2.8 in. aft of the sample leading edge and on the wedge centerline. This instrument recorded the total radiant heat flux emitted from the sample area, and its output was recorded in millivolts. The precision of the recorded signal is estimated to be ±0.015 mv.

The VKF infrared system was used to map the sample surface temperature. The system utilizes an AGA Thermovision® 680 camera which scans at a rate of 16 frames per second. The camera detector is sensitive to infrared radiation in the 3- to 6-μ wavelength band. Camera calibrations are performed with a standard blackbody reference source, have consistently been within ±1 percent of the camera manufacturer's calibration, and are repeatable within ±1 percent in absolute temperature. A description of the VKF system is

given in Ref. 3. The output of the IR camera was displayed on a color TV monitor in real time, and at selected times the monitor was photographed with a 70-mm color still camera.

Color movies (16mm) were taken of the samples intermittently during the run. Shadowgraphs were taken after the samples reached the tunnel centerline and at selected wedge angles to record the flow-field characteristics.

Five Gardon-type heat flux gages were installed in the steel wedge ahead of the samples (see Fig. 2b for locations). These gages had CR-AL thermocouples installed as part of the gage, and the output of the gages provided confirmation of the boundary-layer state on the wedge. The output of the gages was recorded at the same time the output of the sample thermocouples was recorded. A general description of these gages is given in Ref. 2.

3.0 TEST DESCRIPTION

3.1 TEST CONDITIONS AND PROCEDURE

3.1.1 Test Conditions

The desired test conditions on the material samples were obtained by pitching the wedge about 25 deg to the Tunnel C Mach number 10 flow and adjusting the stagnation pressure and temperature. Pretest estimates showed that it would be necessary to set the tunnel stagnation pressure as high as possible at the maximum tunnel stagnation temperature in order to achieve the material temperature of 1,200°F within the 10-min exposure time. Following is a list of the tunnel stagnation conditions and the wedge local flow conditions that existed during the test. A verification of the wedge flow conditions is presented in Section 4.1.

M	p_t, psia	T_t, °R	M_w	p_w, psia	T_w, °R	V_w, ft/sec	$Re_w \times 10^{-6}$, ft^{-1}
10.14	1,200	2,150	3.3	0.083	676	4,207	0.95

A test summary showing all configurations tested and the variables for each is presented in Table 1.

3.1.2 Test Procedure

In the VKF continuous flow wind tunnels [Hypersonic Wind Tunnel (A), Supersonic Wind Tunnel (B), and Tunnel C] the test article is mounted on a sting support mechanism in

an installation tank directly underneath the tunnel test section. The tank is separated from the tunnel by a pair of fairing doors and a safety door. When closed, the fairing doors, except for a slot for the pitch sector, cover the opening to the tank, and the safety door seals the tunnel from the tank area. After the test article is prepared for a data run, the personnel access door to the installation tank is closed, the tank is vented to the tunnel flow, the safety and fairing doors are opened, the model is injected into the airstream, and the fairing doors are closed. After the data are obtained, the test article is retracted into the tank, and the sequence is reversed with the tank being vented to atmosphere to allow access to the test article in preparation for the next run. The sequence is repeated for each configuration change.

The procedure for obtaining the test measurements evolved during the progress of the test. Initially there was concern for the survivability of the cloth samples at wedge angles as large as 25 deg; hence, the wedge was injected at $\delta = 0$ and rotated to 25 deg, while the sample (No. 3 was used) was observed for any indication of failure; the procedure was reversed for retraction. No indications of failure were observed. Next the sample was injected and retracted at $\delta = 25$ deg and again observed for indications of failure. No problems were encountered during injection, but on retraction the top layer of the cloth sample was blown away (see Fig. 6a). It appears the turbulence encountered during retraction through the tunnel wall boundary layer at such a large angle was too severe. A possible explanation of the absence of failure during injection through the same turbulence is that the increased fabric temperature decreased its strength prior to retraction. Consequently, the initial procedure described above was adopted for the remainder of the test.

The samples were exposed to the flow for 10 min each time they were injected. The output of all the instrumentation was recorded every 0.5 sec until the wedge reached the 25-deg pitch angle; then data were recorded every 5 sec for the remainder of the run. The IR system TV monitor was observed, and when the sample surface temperature reached approximately 1,200°F a 70-mm photograph was taken. Another photograph was taken just prior to retraction.

The samples were observed directly during exposure, and whenever any unusual circumstances developed (fabric tears or loose tiles) the 16-mm movie camera was used to record the events. In addition, the injection cycle of each run was recorded on 16-mm film.

After retraction, the sample was cooled by high-pressure air through the tank door nozzle and adjustable manifolds on each side. Also, the steel wedge has internal water-cooling passages which aided in cooling the sample. Whenever the sample's aluminum support plate cooled to 150°F, the sample was injected for another run or was replaced by

another sample. The nominal temperatures of the tiles at injection ranged from 70 to 140°F. Any damage to the samples was photographed using a 70-mm camera prior to continued testing (see Fig. 6b).

Each exposure is termed a run, and all the data obtained are identified in the data tabulations by run number. The samples tested during each run are listed in Table 1.

3.2 DATA REDUCTION

3.2.1 IR System Photographs of Sample Surface Temperature

The calibration of the IR system itself is detailed in Ref. 3, and the only other information required to obtain the sample surface temperature is the surface emissivity.

A representative sample of the fabric insulation was examined to determine its emissivity over the range from 3 to 6 μ. The results are presented in Fig. 7. The sample total emissivity was computed by the equation

$$\epsilon = \frac{\int_3^6 \left(\epsilon_\lambda\right)\left(e_{b_\lambda} X_\lambda\right) d\lambda}{\int_3^6 \left(e_{b_\lambda} X_\lambda\right) d\lambda} \tag{1}$$

where

ϵ_λ = sample spectral emissivity from Fig. 7 at 530° R

e_{b_λ} = blackbody spectral emissivity at 530° R

X_λ = IR camera spectral response factor obtained from the manufacturer

Both e_{b_λ} and (e_{b_λ} X_λ) variations with wavelength over the range of interest are presented in Fig. 8a, and (e_λ) (e_{b_λ} x_λ) variations are shown in Fig. 8b. The values of the integrals are shown in the figures; from these the sample total emissivity was computed to be 0.62. For this emissivity, the color calibration with temperature for the photographs of the IR system TV monitor is listed in Table 2.

3.2.2 Sample Temperatures

Because of the expense of platinum wire, the thermocouple leads were only about 12 in. long and terminated at a 50-pin connector inside the wedge support. Copper leads were used

from the other side of the connector to the instrumentation. The output of the sample thermocouples was dependent upon the connector temperature with this type of hookup; hence, the temperature at two locations (T_{R1} and T_{R2}) on the connector were measured using CR-AL thermocouple wire. The connector temperatures were measured with direct readout instruments in °F.

The total output of each thermocouple was computed by first calculating the equivalent platinum millivolt output of the connector thermocouple using the following equation:

$$\begin{aligned} E_R &= 0.42282 + \left(2.66830 \times 10^{-3}\right) T_{R1} \\ &\quad + \left(4.49139 \times 10^{-6}\right)\left(T_{R1}\right)^2 - \left(3.5078 \times 10^{-9}\right)\left(T_{R1}\right)^3 \\ &\quad + \left(1.40615 \times 10^{-12}\right)\left(T_{R1}\right)^4 \end{aligned} \tag{2}$$

where

E_R = equivalent millivolt output of a platinum thermocouple at temperature T_{R1}

T_{R1} = measured connector temperature in °F

The second connector temperature (T_{R2}) was used as a redundant measurement. The equivalent millivolt output (E_R) was added to the output of each platinum thermocouple to obtain the total millivolt output of each thermocouple (E_{TC}). The temperature for each platinum thermocouple was then computed from the equation

$$TC_i = A_0 + A_1\left(E_{TC_i}\right) + A_2\left(E_{TC_i}\right)^2 + \ldots + A_N\left(E_{TC_i}\right)^N \tag{3}$$

where the coefficients A_0 ..., A_N are defined below and "i" denotes the TC number.

Range of E_{TC_i}, mv	A_0	A_1	A_2	A_3	A_4	A_5
$-0.422 \leq E_{TC} \leq 1.175$	591.727	270.981	-11.8644	53.7323	-37.7430	11.9930
$1.175 \leq E_{TC} \leq 5.604$	605.398	234.610	-17.7323	2.18924	-0.122826	---
$5.604 \leq E_{TC} \leq 11.024$	657.117	192.452	-3.8197	0.0687992	---	---

3.2.3 Heat-Transfer Measurements

The output of the Gardon-type heat gages was converted to heat flux by the equation

$$\dot{q} = (SF)(\Delta E) \tag{4}$$

where ΔE is the measured gage output in millivolts and SF is the gage scale factor determined from direct measurements of the gage output for a known radiant heat flux input. The heat-transfer coefficient was then computed by the equation

$$h_o = \frac{\dot{q}}{T_t - T_g} \tag{5}$$

where T_t is the tunnel total temperature and T_g is the gage temperature.

3.3 UNCERTAINTY OF MEASUREMENTS

3.3.1 General

The accuracy of the basic measurements (p_t and T_t) was discussed in Section 2.3. On the basis of repeat calibrations, these errors were found to be

$$\frac{\Delta p_t}{p_t} = 0.0016 = 0.16 \text{ per cent}$$

$$\frac{\Delta T_t}{T_t} = 0.004 = 0.4 \text{ per cent}$$

Uncertainties in the tunnel free-stream parameters and the model temperatures were estimated using the Taylor series method of error propagation, Eq. (6),

$$(\Delta F)^2 = \left(\frac{\partial F}{\partial X_1}\,\Delta X_1\right)^2 + \left(\frac{\partial F}{\partial X_2}\,\Delta X_2\right)^2 + \left(\frac{\partial F}{\partial X_3}\,\Delta X_3\right)^2 \cdots + \left(\frac{\partial F}{\partial X_n}\,\Delta X_n\right)^2 \tag{6}$$

where ΔF is the absolute uncertainty in the dependent parameter $F = f(X_1, X_2, X_3 \ldots X_n)$ and X_n represents the independent parameters (or basic measurements). The term ΔX_n represents the uncertainties (errors) in the independent measurements (or variables).

3.3.2 Tunnel Conditions

The accuracy (based on 2σ deviation) of the basic tunnel parameters, p_t and T_t (see Section 2.3) and the 2σ deviation in Mach number determined from test section flow calibrations were used to estimate uncertainties in the other flow parameters using Eq. (6). The computed uncertainties in the tunnel free-stream and wedge flow parameters are summarized below.

Uncertainty, (±) Percent of Computed Value					
M	M_w	P_w	T_w	V_w	Re_w
0.8	2.5	6.3	3.5	6.3	2.9

3.3.3 Test Data

The uncertainties of the test data parameters are summarized below.

Data Type	Uncertainty, (±) percent of actual value
IR Color Boundary* Temperature	1.00
Ames Radiometer Output	0.14
Sample Temperature at 1,660°R	0.35
Connector Temperature at 575°R	0.67
Gardon Gage Heat Flux, $\dot{q}$, Btu/ft^2-sec	5.00
Gardon Gage Temperature, T_g, °R	0.50
Gardon Gage Heat Transfer Coefficient, h_o, Btu/ft^2-sec°R	6.00

* See Fig. 11 for color/temperature calibration

4.0 RESULTS AND DISCUSSION

The purpose of this report is to present a description of the test technique used to achieve the test objectives and to present some typical test results. The test technique used is described in Section 3.0; the wedge surface flow conditions (corresponding to the material sample local flow conditions) are verified and typical results are presented in this section.

4.1 SAMPLE TEST ENVIRONMENT

Shown in Fig. 9 is a shadowgraph of the flow over the sample surface. Several shocks evidently are emanating from the quilted pattern in the fabric. The inclination of these shocks is taken to be the Mach angle of the surface Mach number. From measurements of the angles of the first and last shock that are visible in Fig. 9, the surface Mach number was computed to be approximately 3.3. This Mach number corresponds to a wedge angle of 25.5 deg for the free-stream Mach number of 10.14. The indicated wedge angle was set to 24.5 deg; an additional degree of deflection apparently was produced by the aerodynamic loads. From the wedge surface Mach number and tunnel stagnation conditions all the remaining surface conditions may be computed.

The computed surface flow conditions together with a finite difference procedure outlined in Ref. 4 were used to calculate the surface heat-transfer coefficient and shear distributions. It was assumed that transition occurred at the roughness location for the turbulent case. The results are presented in Figs. 10a and b along with measurements from the heat gages installed in the wedge ahead of the samples. It is seen from Fig. 10a that the measured heat-transfer results agree well with computed values. The inferred shear values from the heat gage measurements were computed from the equation below for a Prandtl number of one.

$$\tau = 0.117\, h_o\, V_w \tag{7}$$

4.2 TEST RESULTS

The sample surface temperature was monitored using the IR camera — a picture was taken whenever a region of the sample reached 1,200°F, and another was taken at the end of the 10-min test period just prior to retraction. A typical picture of this type is presented in Fig. 11. The temperatures associated with each color boundary are indicated on the picture. This temperature calibration was determined using an emissivity of 0.62 for the fabric samples and should be used to infer temperature for only the fabric portion of the sample surface.

To obtain the surface temperatures of the ceramic RSI tiles it would be necessary to know the emissivity of those surfaces and adjust the IR camera temperature calibration for the change. Shown in Fig. 12 are plots depicting the variation with emissivity of the temperatures associated with each color number. The ceramic RSI tiles were not available for pretest measurements of their emissivity values.

Typical measured sample thermocouple temperatures are presented as a function of time in Fig. 13 for Run 23. Also presented in Fig. 13a are (1) the IR camera indicated fabric surface temperature at approximately the center of the fabric sample (see Fig. 11) and (2) the computed fabric surface equilibrium temperature (1,630°R). The computed value was obtained by a one-dimensional conduction code (Ref. 5), a brief description of which is presented in Appendix A. The IR camera results show that the fabric surface reached the desired temperature and agrees quite well with the predicted equilibrium value. The temperature just under the top layer of fabric (TC_{14}) is about 200°F less than the surface temperature indicated by the IR camera. This difference illustrates the necessity of having an external measurement of the surface temperature in materials evaluation tests of this type. It would be difficult to install a surface thermocouple in a 0.010-in. layer of glass cloth and obtain a true surface temperature.

The heat from the surface did not penetrate through the fabric sample until about 200 sec after exposure. This is indicated by TC_{11}, which shows the rise was only about 100°F at the end of the exposure cycle. Even then a difference of about 1,000°F was maintained between the exposed and interior surfaces of the insulation over its 1-in. thickness. The temperatures at the thermocouple locations in the ceramic RSI tiles are presented in Fig. 13b. The thickness of these tiles was not available to allow evaluations similar to those of the fabric sample. However, it is of interest to note that thermocouples located on the edges of the tiles rose to higher equilibrium values than the thermocouples near the center of the tiles. The temperature-time data shown in Fig. 13 are typical for Sample 2.

The performance of the samples in terms of reusability did not indicate any serious defects. Sample 2 underwent 15 different exposures with only moderately visible "wear and tear." Sample 3 was damaged (see Fig. 6a and Section 3.1.2) for unrelated reasons, Sample 1 showed a little fraying of one of the edges and was withdrawn from use to allow posttest examination, and Sample 4 experienced a tear down the center of both fabric samples (see Fig. 6b) which may have been related to handling. The preliminary analysis indicates that the reusability of the materials is good for the test environment to which the samples were subjected during these tests. However, a detailed analysis will be done by NASA/ARC.

5.0 CONCLUDING REMARKS

Wind tunnel tests were conducted to determine the thermal response and reusability of AFRSI and ceramic RSI thermal protection materials. The materials were subjected to a convective heating environment which heated their surface to 1,200°F. The materials were exposed for a total of 10 min on each injection with one sample being injected 15 times. The

test environment was produced by a wedge at a 25-deg angle in the AEDC/VKF Mach 10 Hypersonic Wind Tunnel (C). The results of the tests may be summarized as follows:

1. The materials testing technique developed at AEDC provided a clean convective heating environment which subjected the materials samples to the required test conditions without any undesirable side effects (i. e., particle contamination) to distort the results.

2. The temperature measured with a thermocouple under the top layer of fabric (0.010 in. thick) of the AFRSI material sample was 200°F less than the surface temperature measured by the VKF IR system. This difference emphasizes the value of having an external measurement of the material surface temperature in evaluation tests of this type.

3. The temperature measurements on an AFRSI sample, which was about 1 in. thick, indicated a 1,000°F difference between exposed and interior surfaces.

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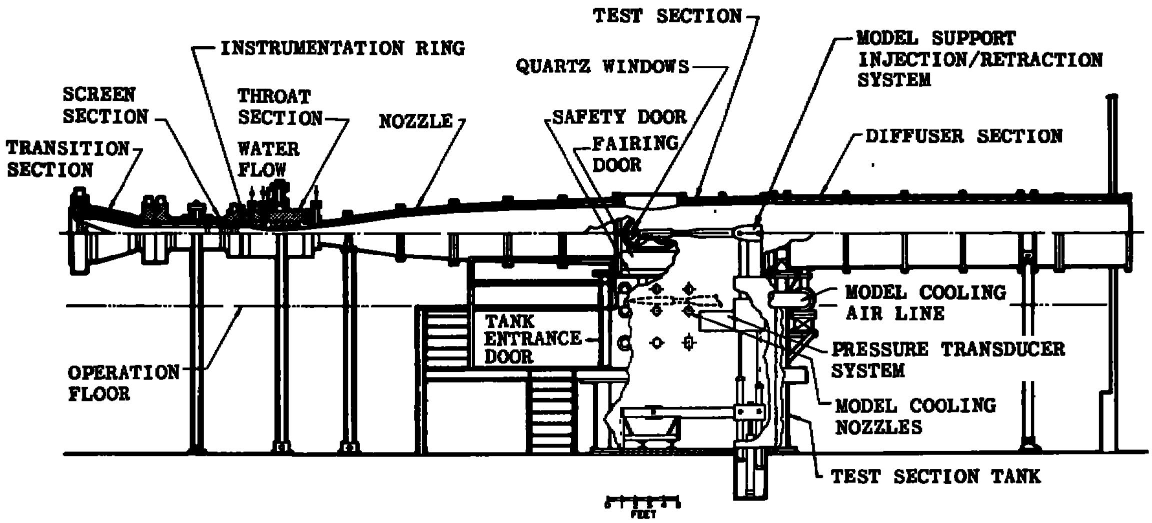
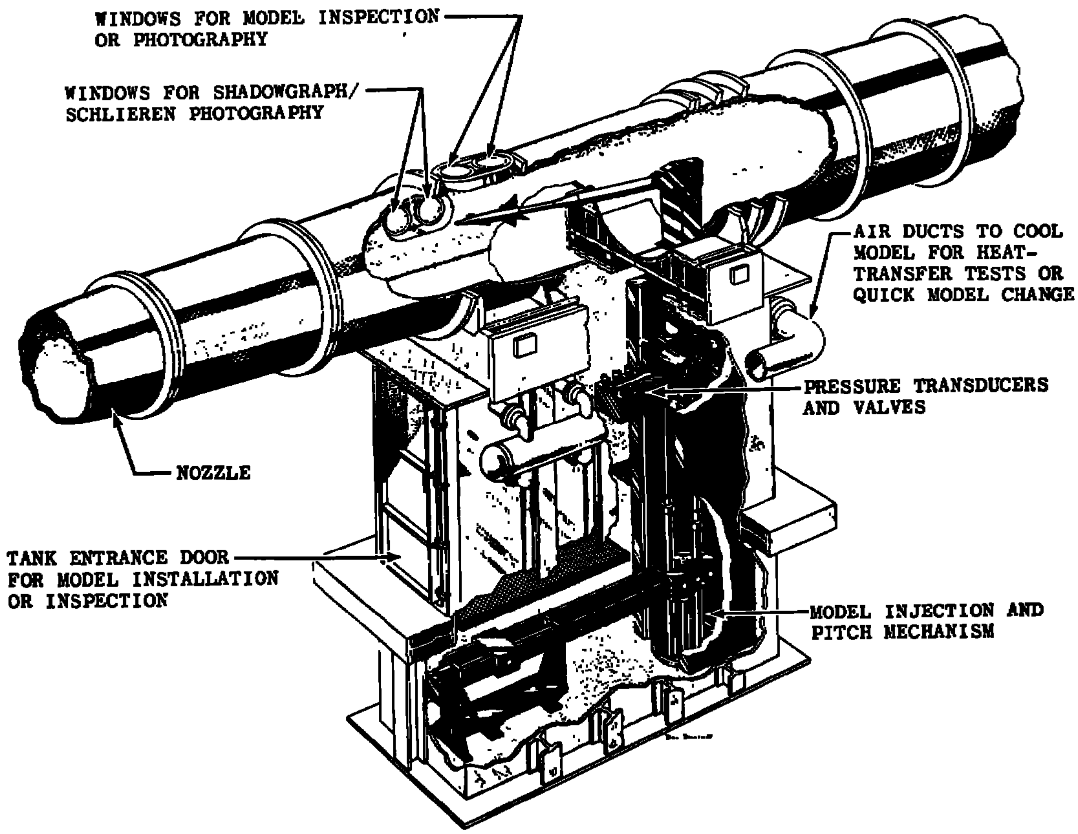
5. Marchand, E. O. "One Dimensional, Transient Heat Conduction in Composite Solids." M.S. Thesis, University of Tennessee, August 1974.

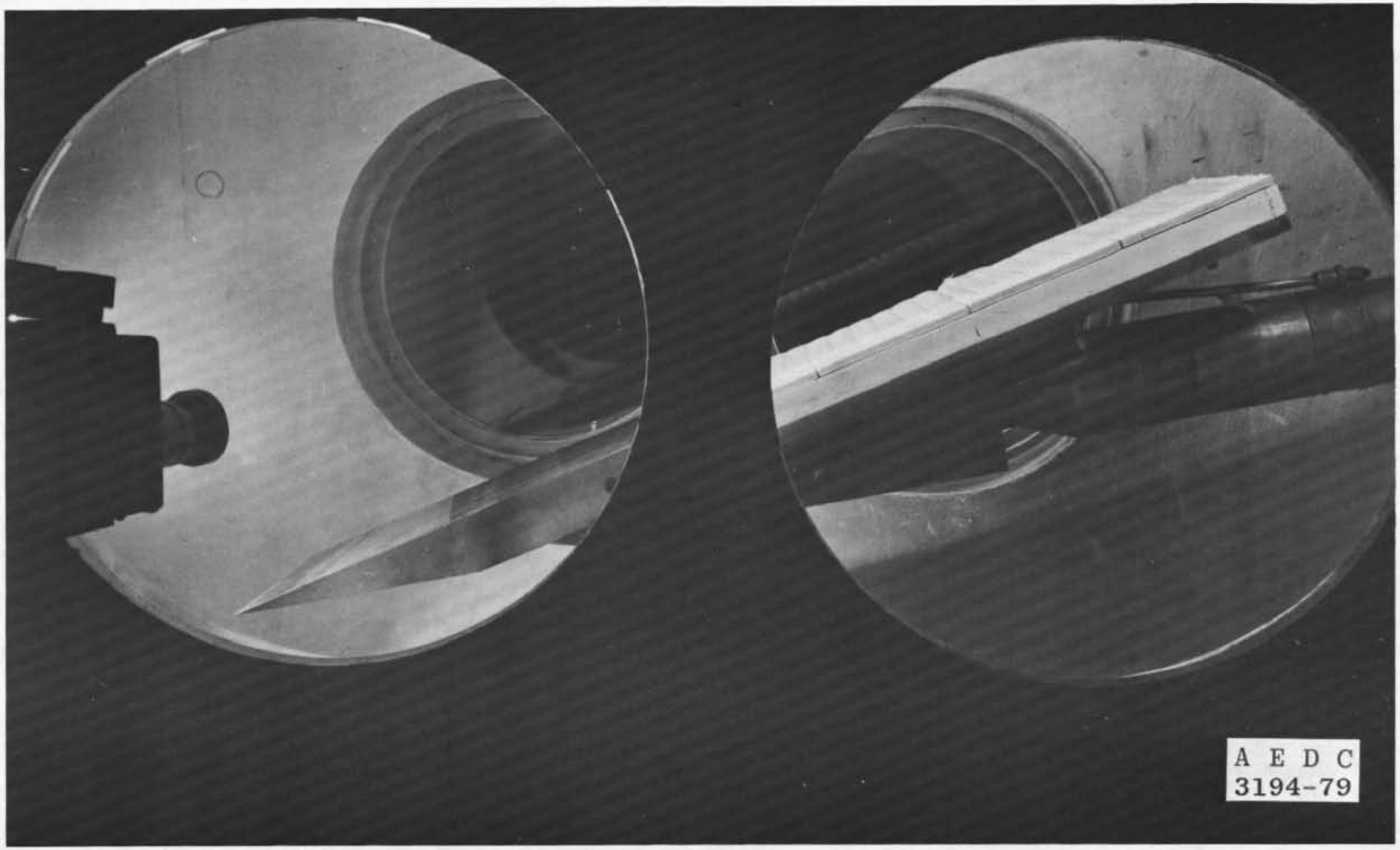


a. Tunnel assembly

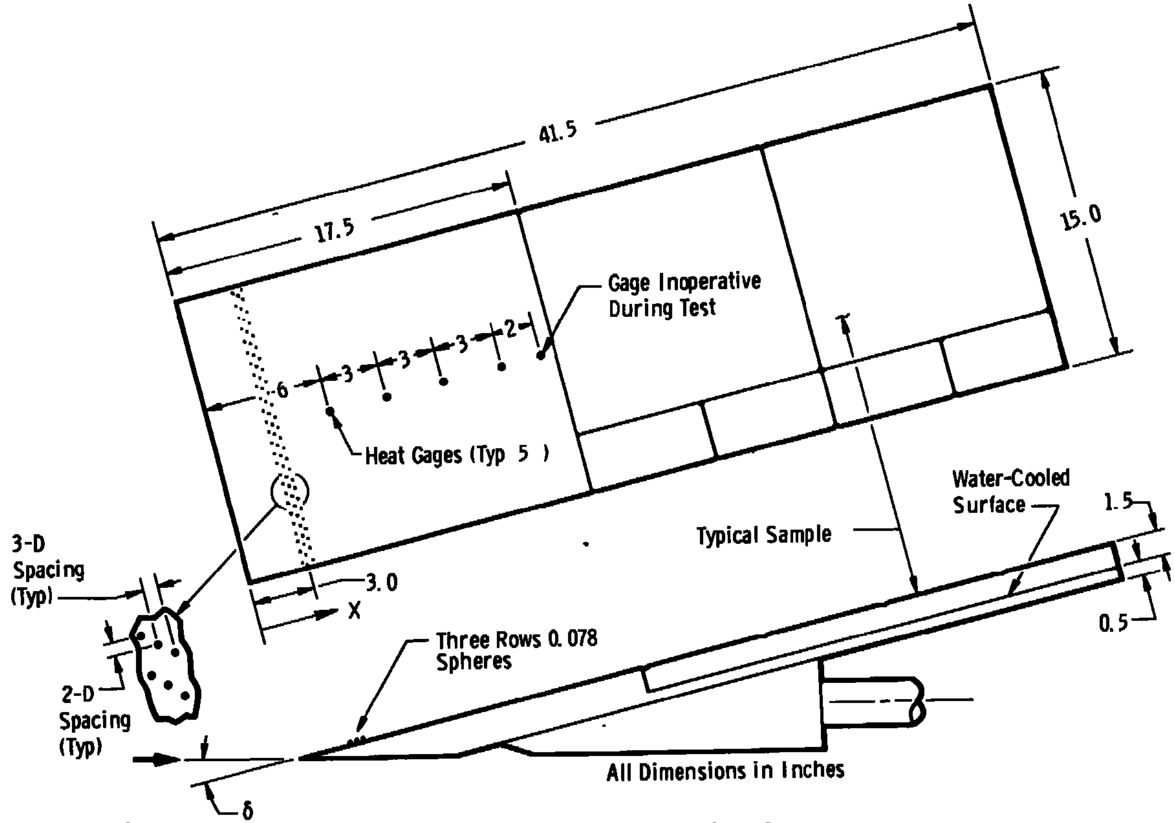


b. Tunnel test section

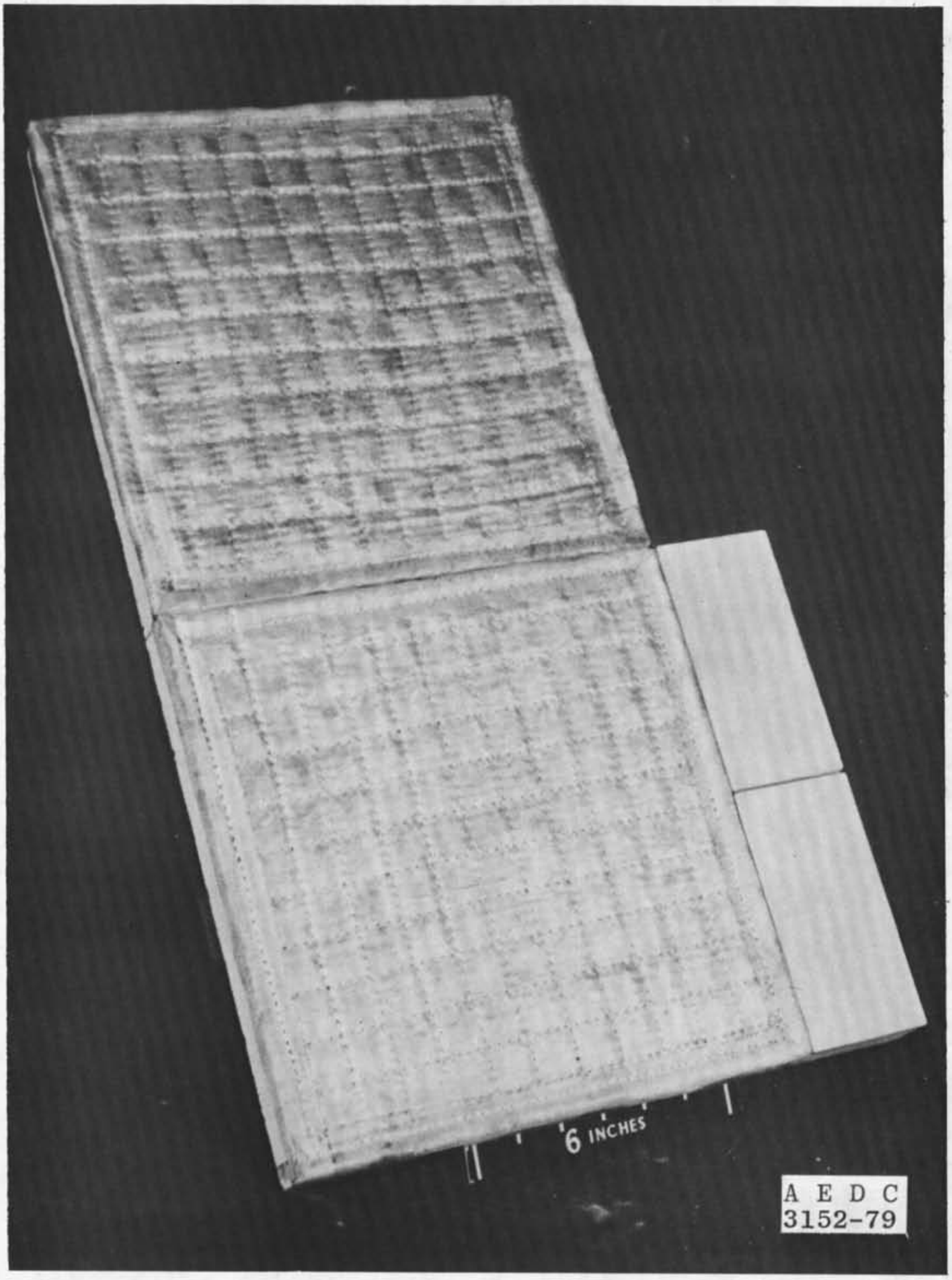
Figure 1. Tunnel C.



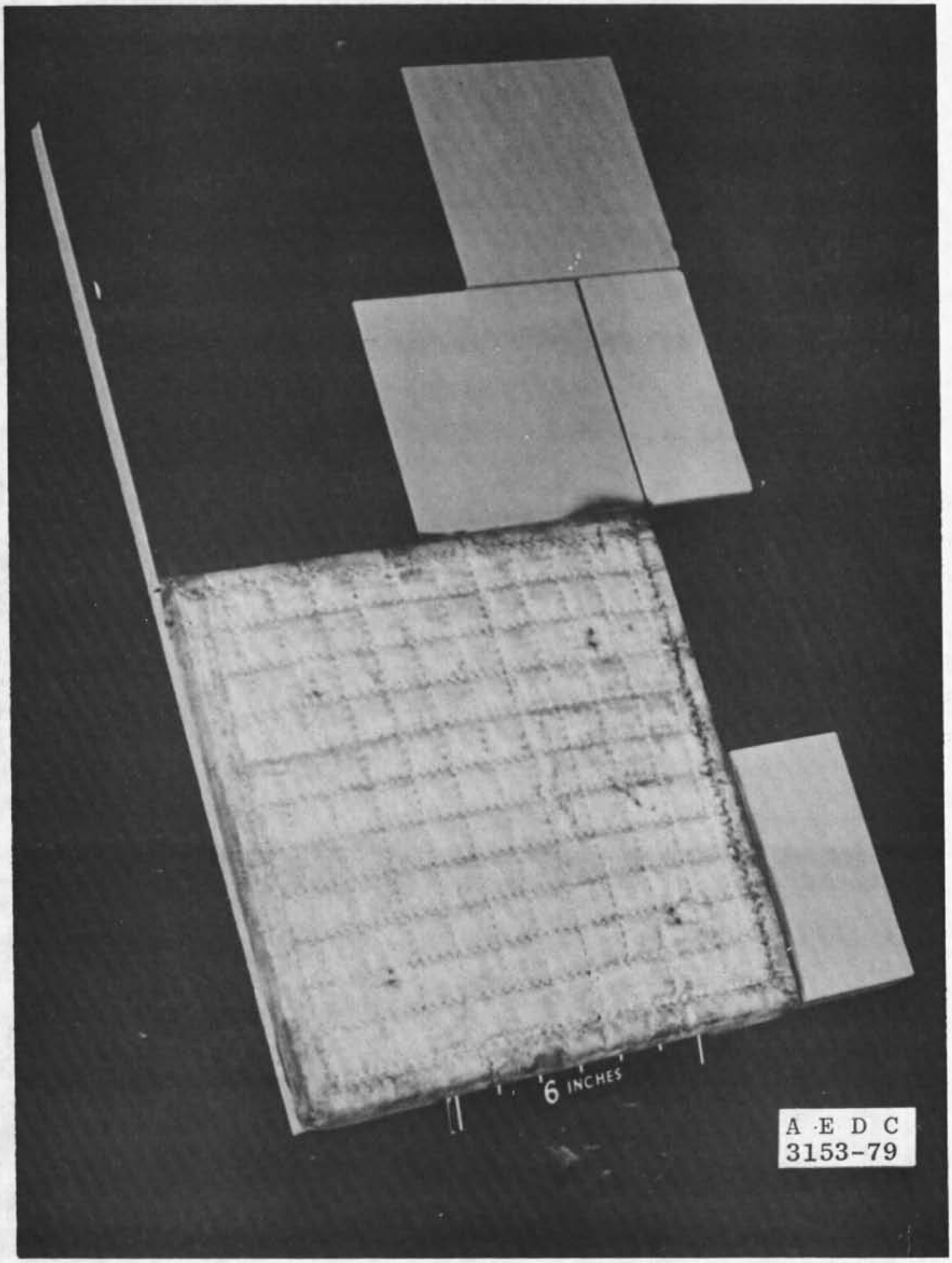
a. Installation photograph
Figure 2. Installation photograph and sketch.



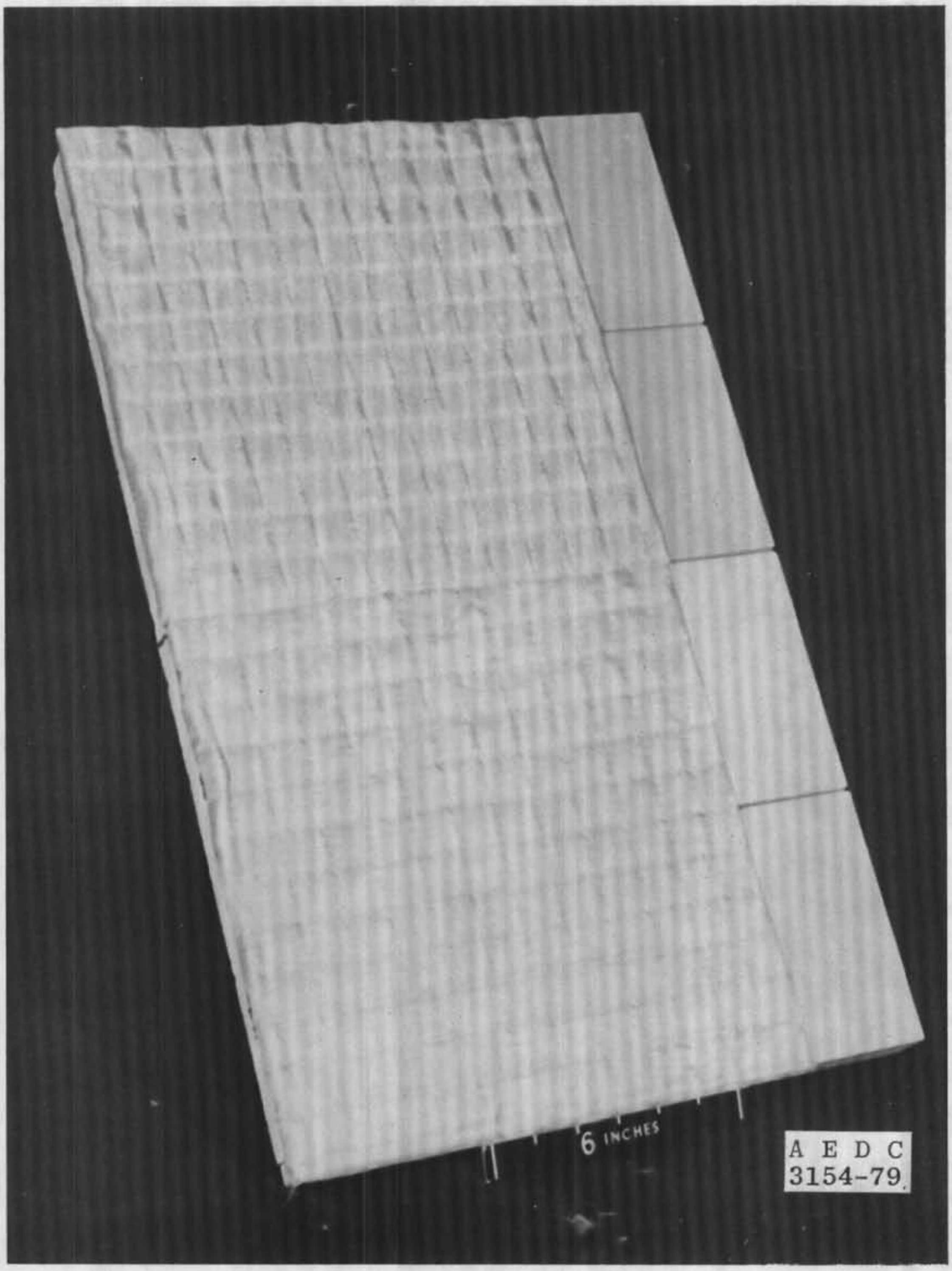
b. Installation sketch
Figure 2. Concluded.



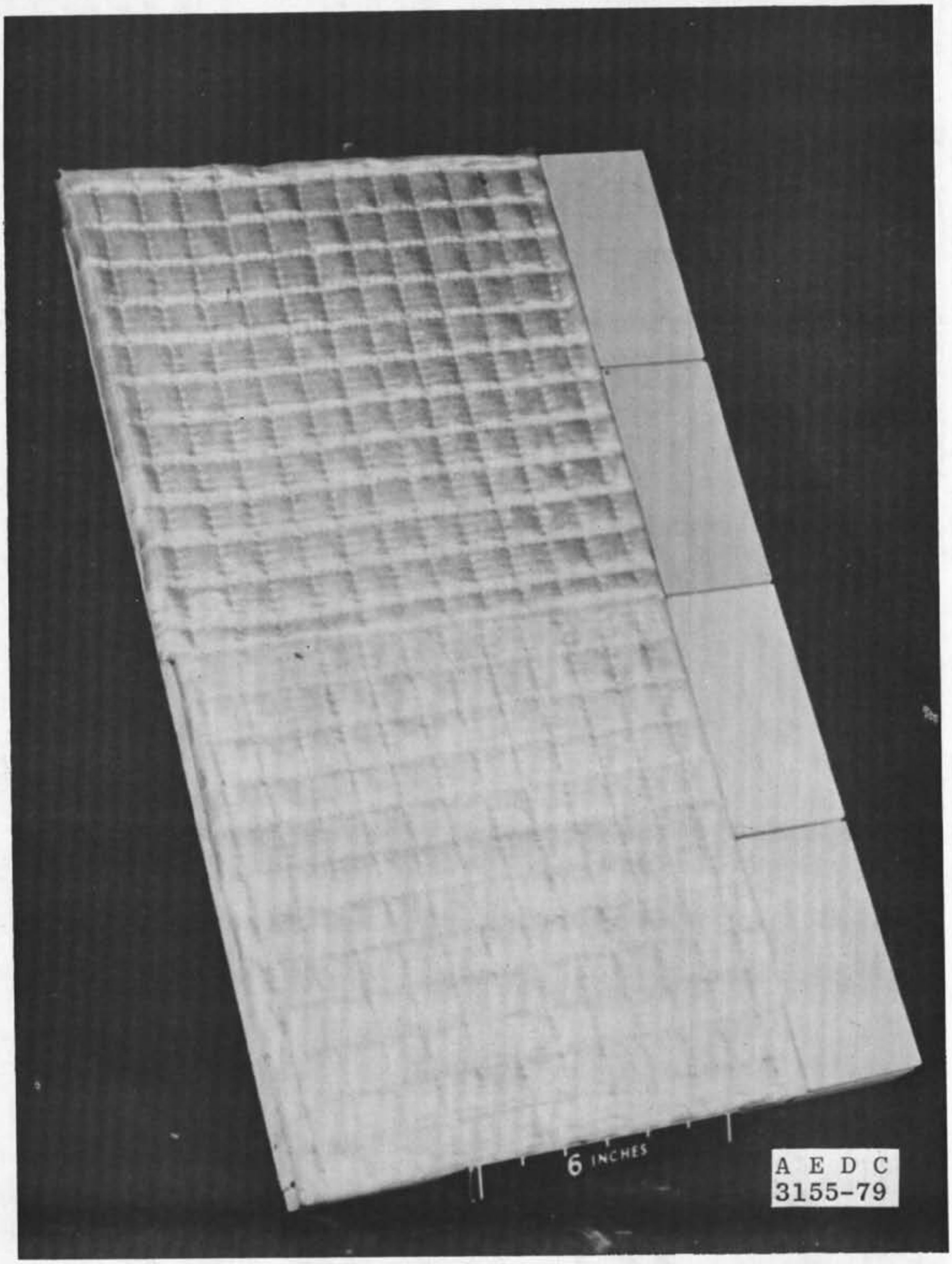
a. Sample No. 1
Figure 3. Photographs of test samples.



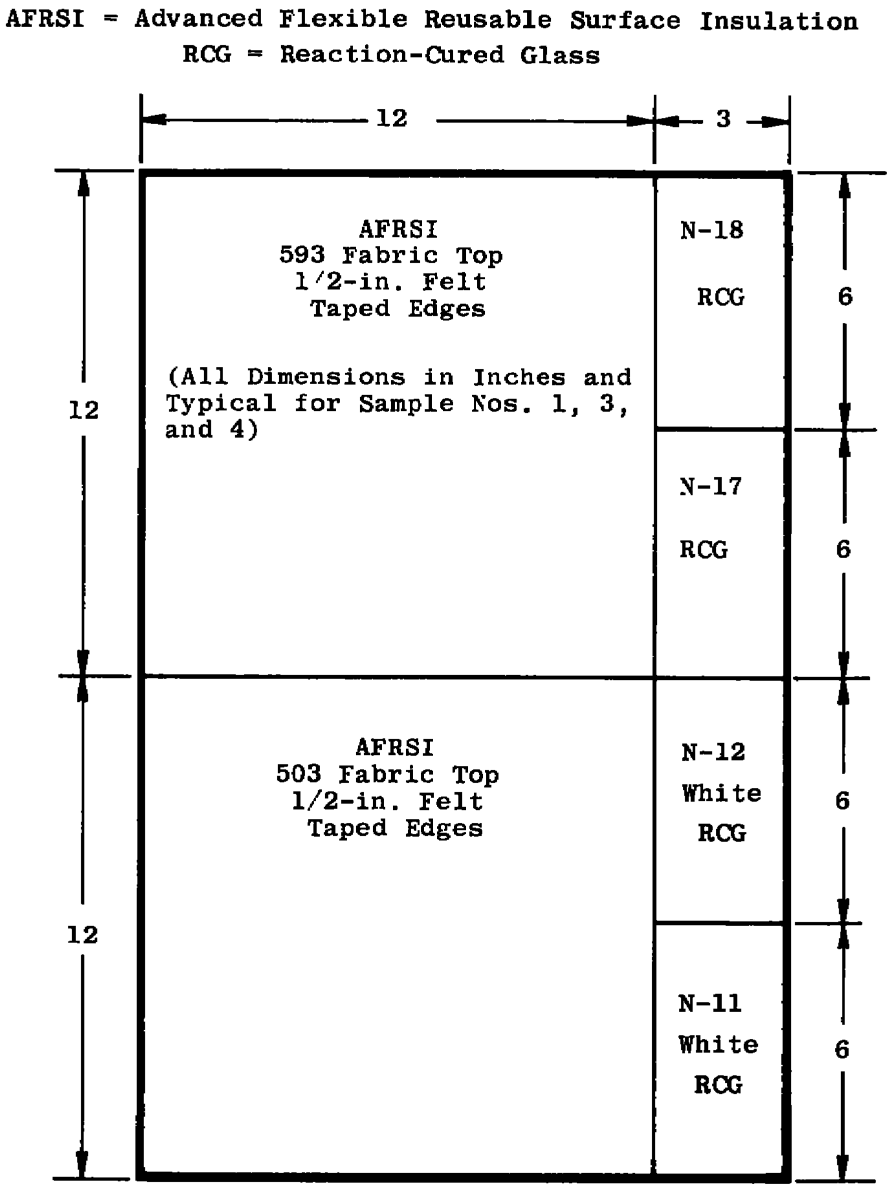
b. Sample No. 2
Figure 3. Continued.



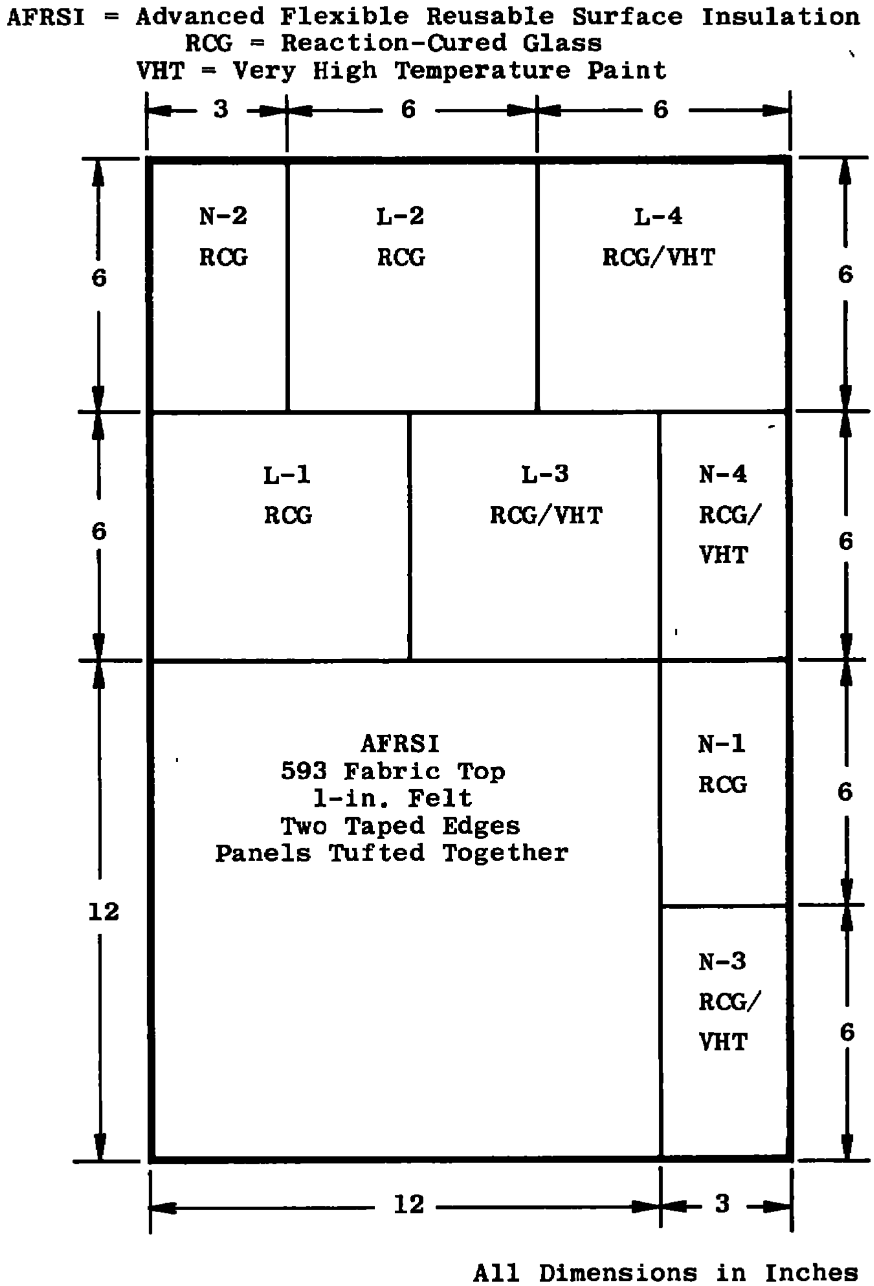
c. Sample No. 3
Figure 3. Continued.



d. Sample No. 4
Figure 3. Concluded.



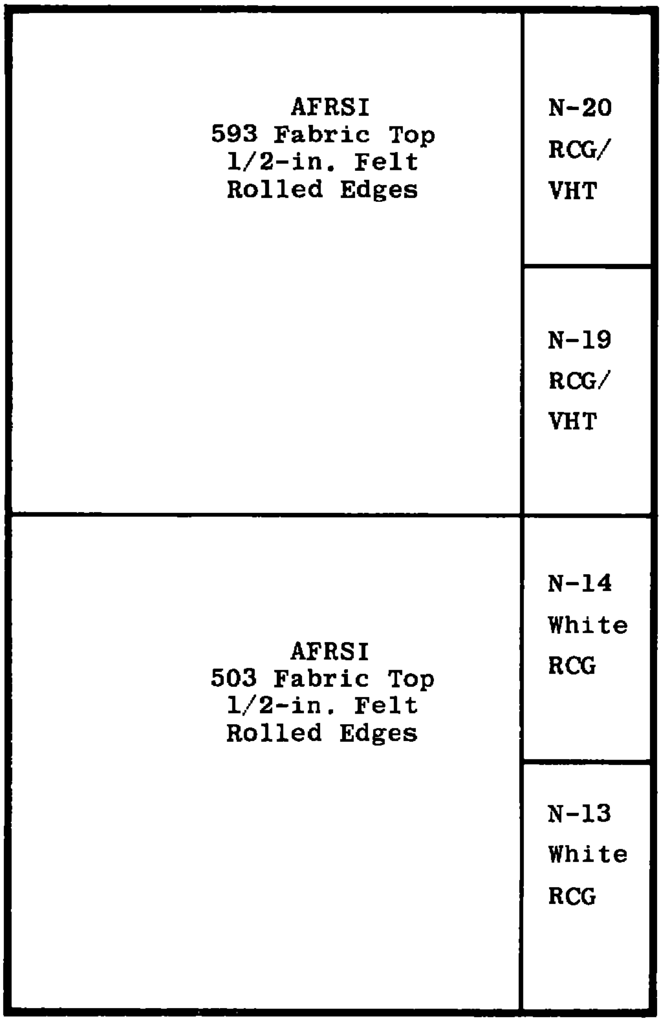
a. Sample No. 1
Figure 4. Details of test samples.



b. Sample No. 2

Figure 4. Continued.

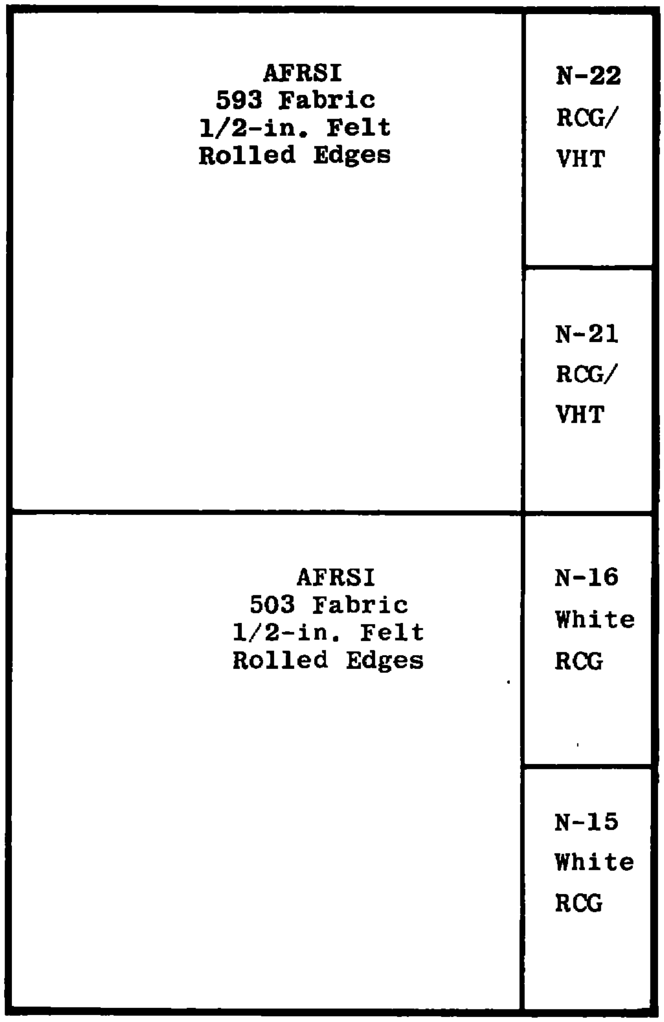
AFRSI = Advanced Flexible Reusable Surface Insulation
RCG = Reaction-Cured Glass
VHT = Very High Temperature Paint



See Fig. 3a for Dimensions

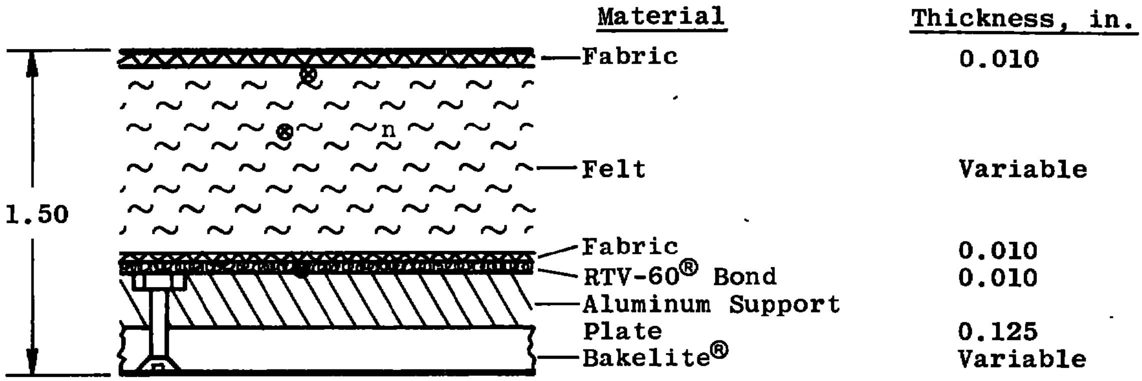
c. Sample No. 3
Figure 4. Continued.

AFRSI = Advanced Flexible Reusable Surface Insulation
RCG = Reaction-Cured Glass
VHT = Very High Temperature Paint



See Fig. 3a for Dimensions

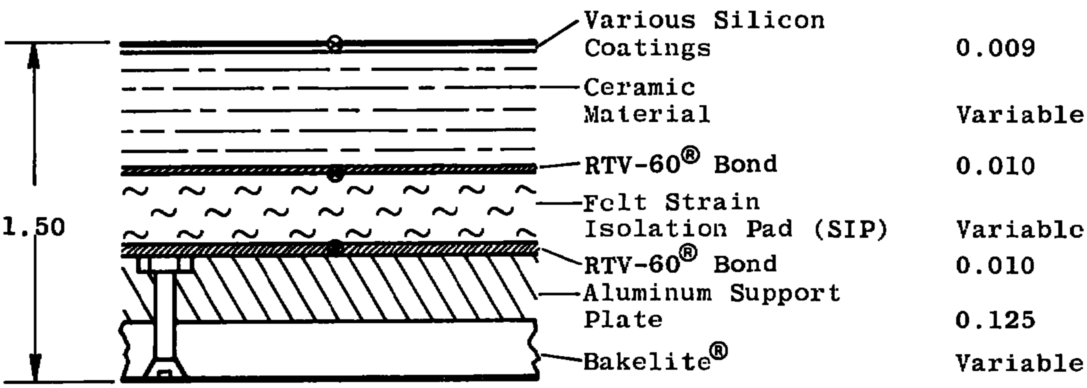
d. Sample No. 4
Figure 4. Continued.



1. AFRSI Material

⊗ Typical Thermocouple Locations)

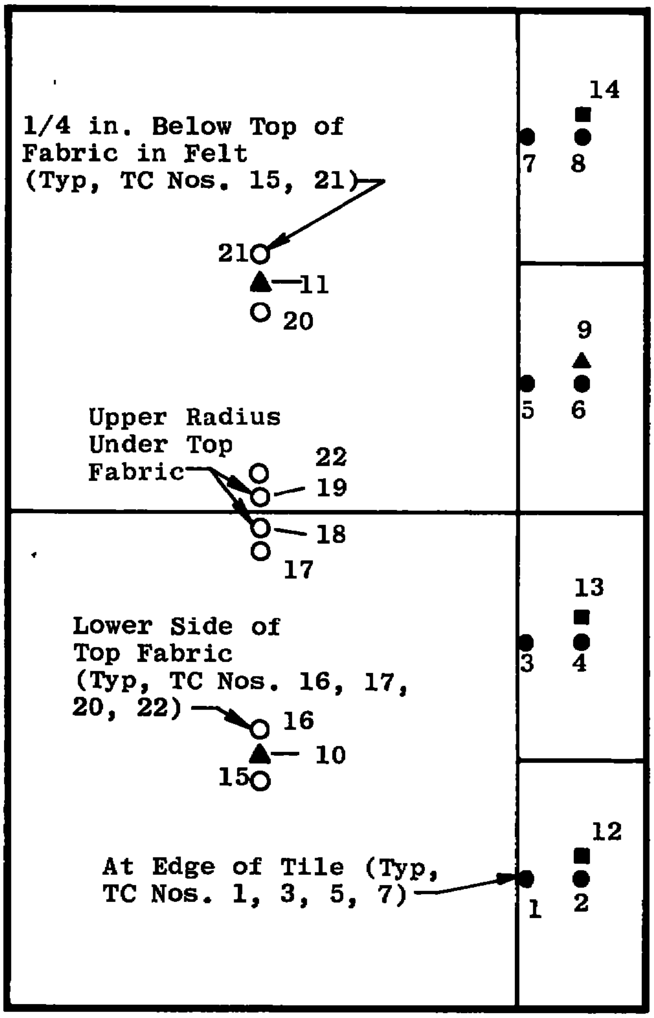
All Dimensions in Inches



2. Ceramic RSI Tiles

e. Typical construction of AFRSI and RSI samples
Figure 4. Concluded.

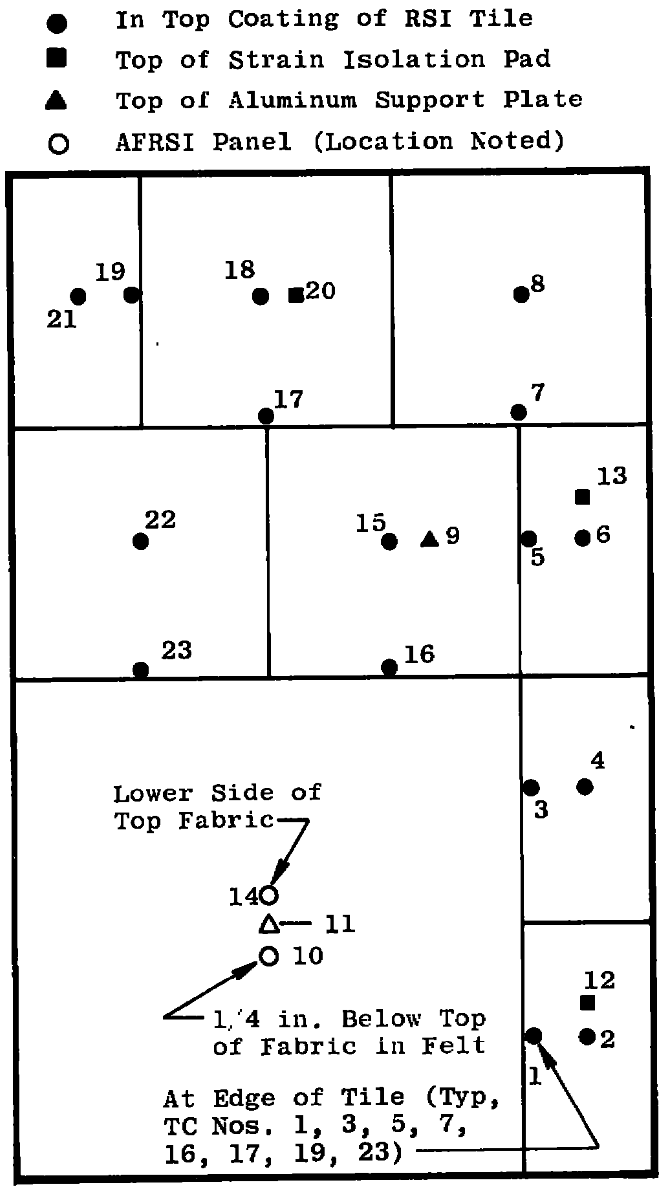
● In Top Coating of RSI Tile
■ Top of Strain Isolation Pad
▲ Top of Aluminum Support Plate
○ AFRSI Panel (Location Noted)



See Fig. 3a for Dimensions

Note: Thermocouple locations shown are approximate.

a. Sample Nos. 1, 3, and 4
Figure 5. Thermocouple locations in test samples.



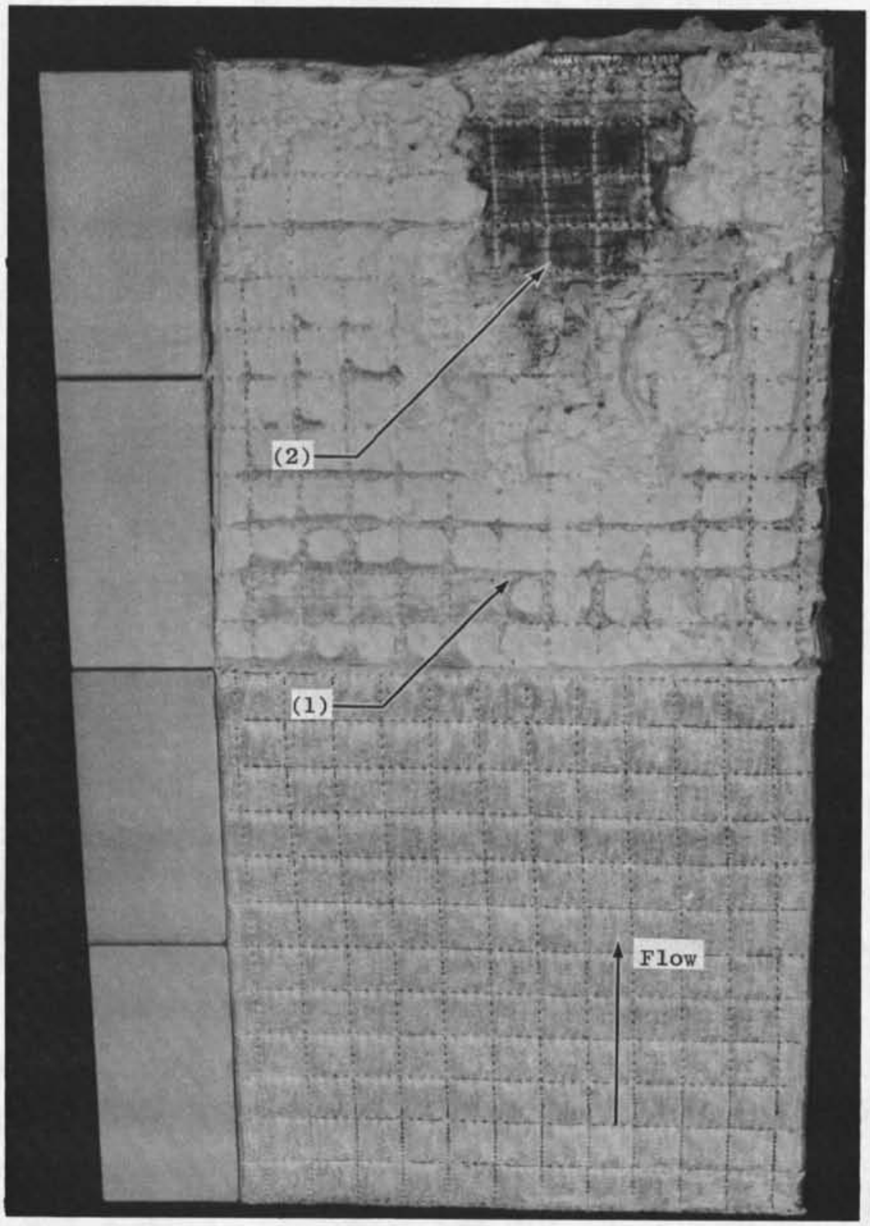
See Fig. 3a for Dimensions

Note: Thermocouple locations shown are approximate.

b. Sample No. 2
Figure 5. Concluded.

Damage Consisted of:

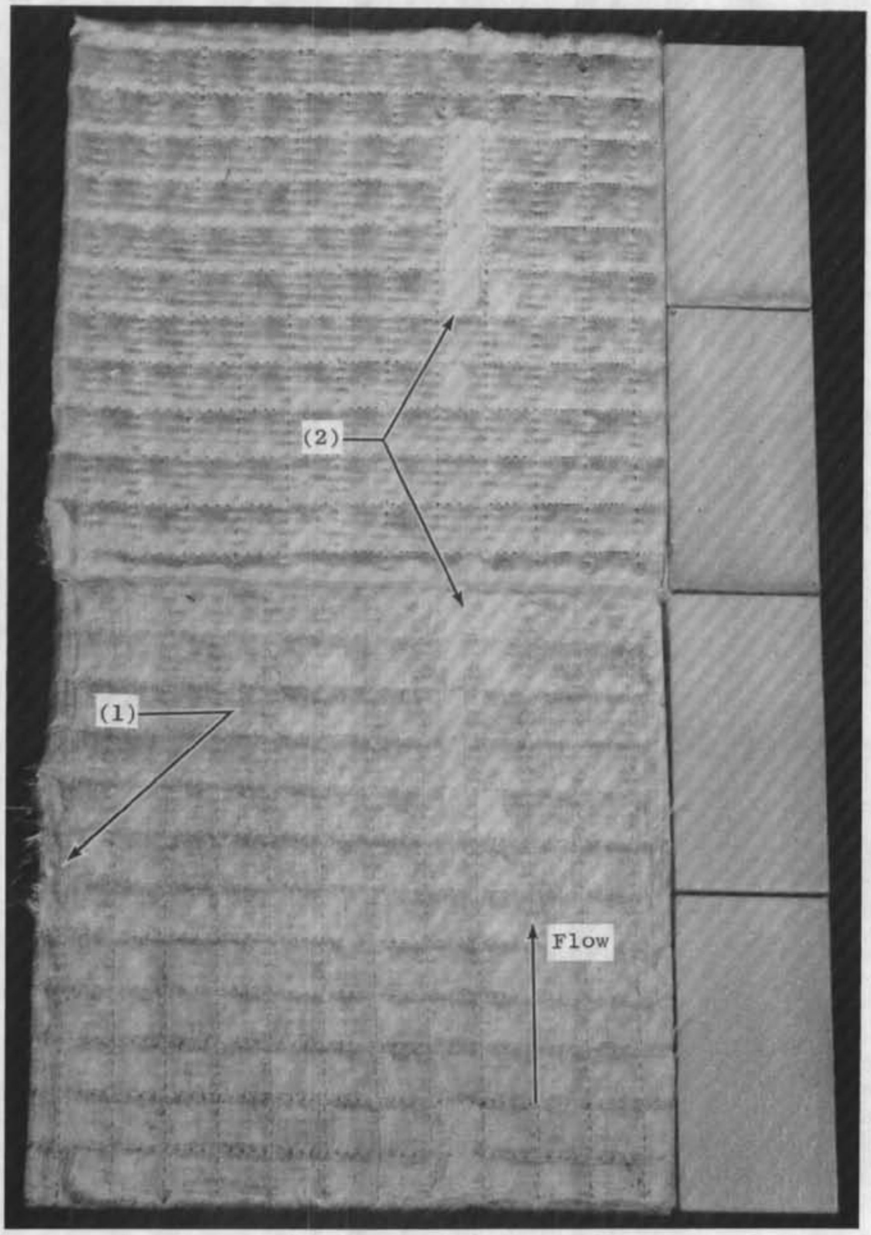
(1) Ripping Off Top Fabric Layer
(2) Tearing Away Felt Insulation, Exposing Bottom Fabric Layer



a. Sample 3 after Run 1
Figure 6. Photographs of damaged samples.

Damage Consisted of:

(1) Fraying Edge
(2) Ripping Off Top Fabric Layer across Both Panels



b. Sample 4 after Run 18
Figure 6. Concluded.

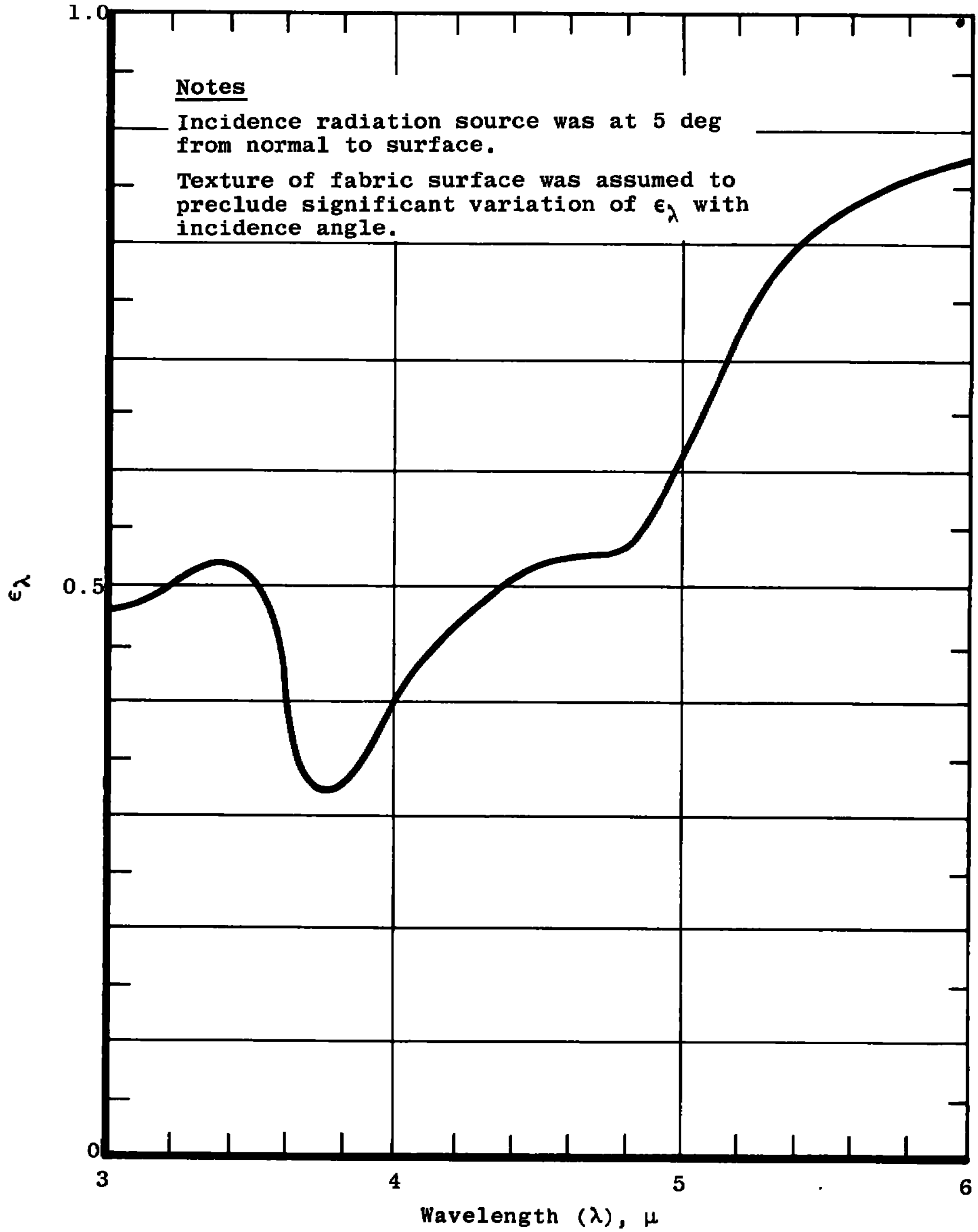
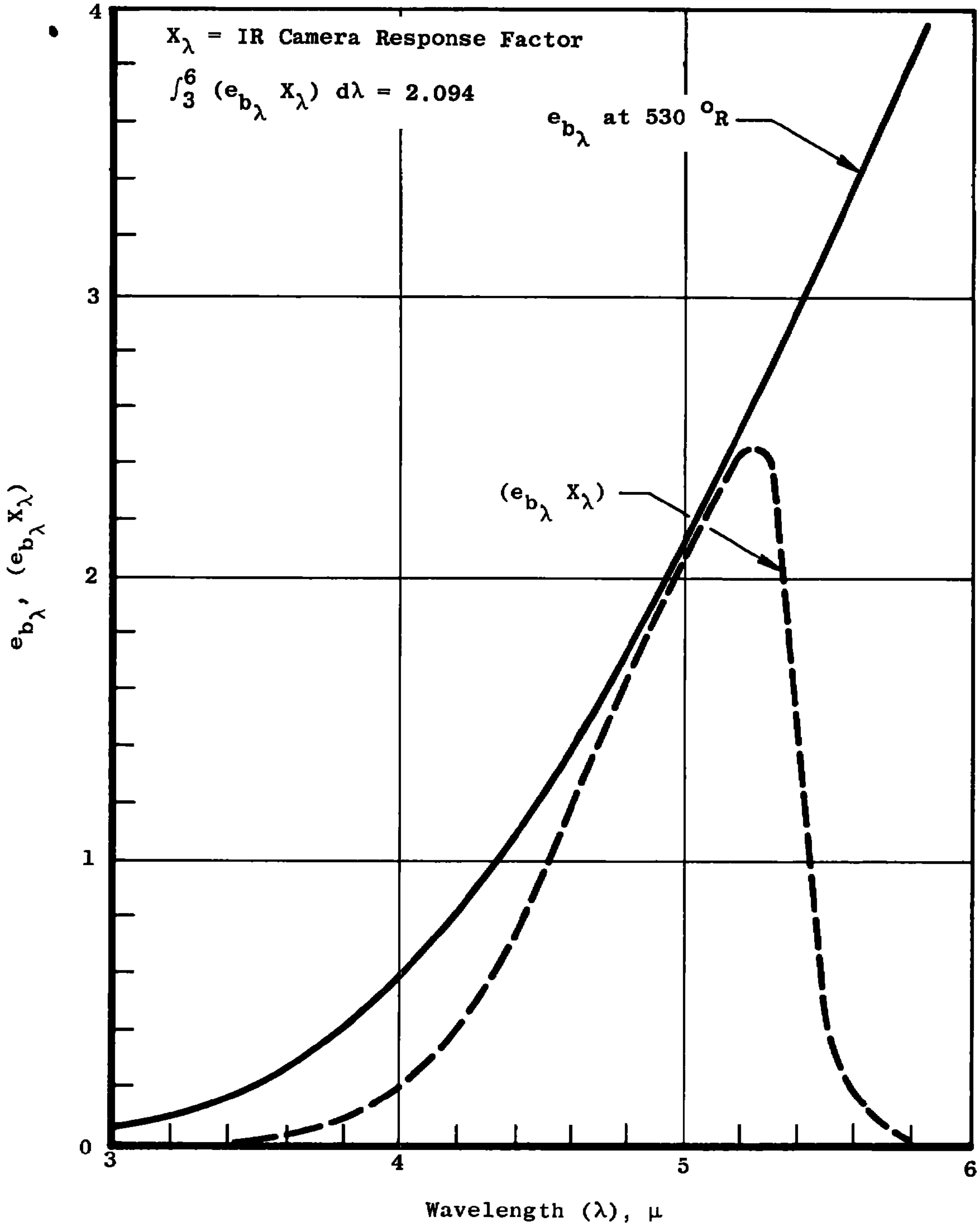
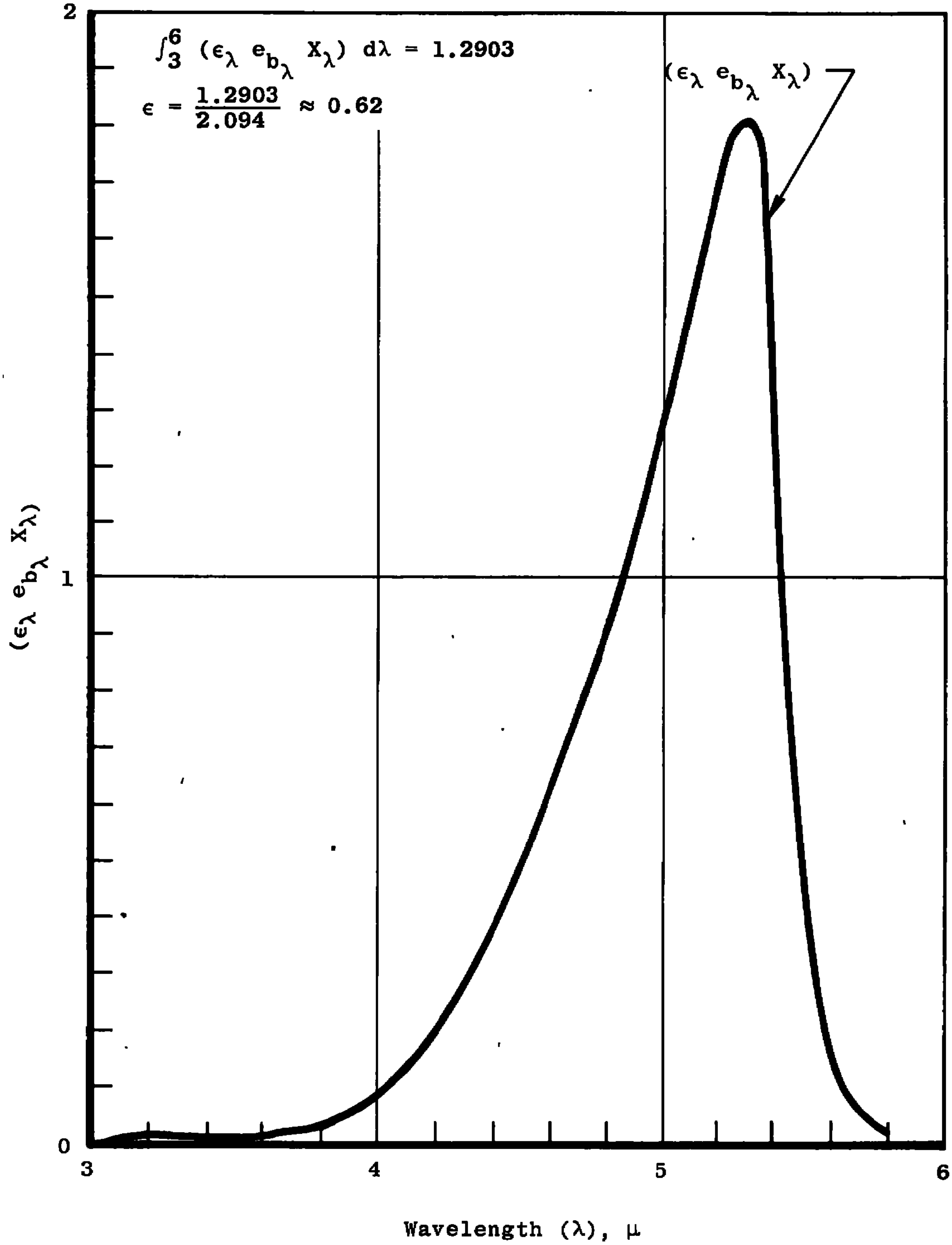


Figure 7. AFRSI spectral emissivity.



a. Blackbody emissivity

Figure 8. Blackbody and AFRSI total emissivity.



b. AFRSI sample total emissivity
Figure 8. Concluded.

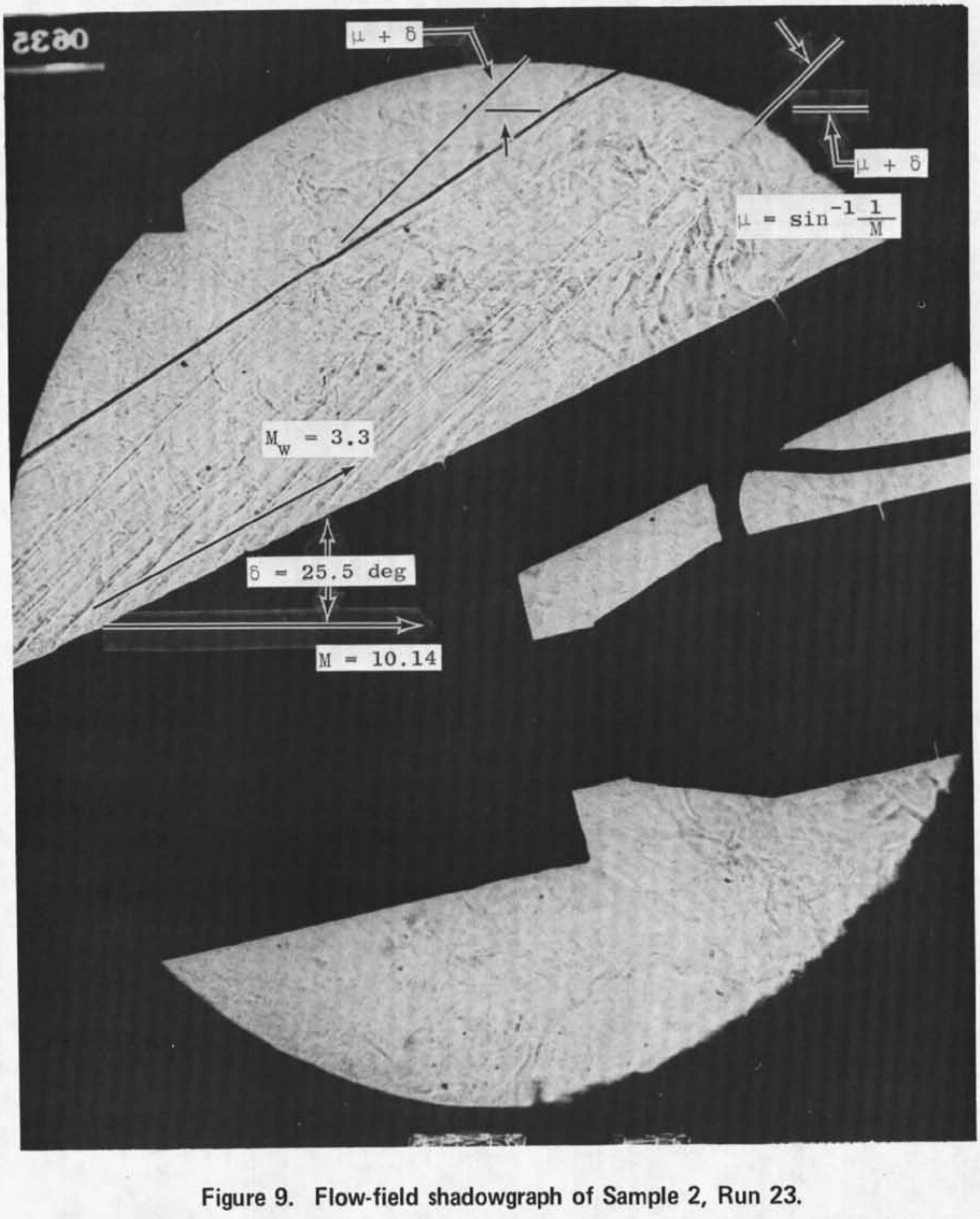
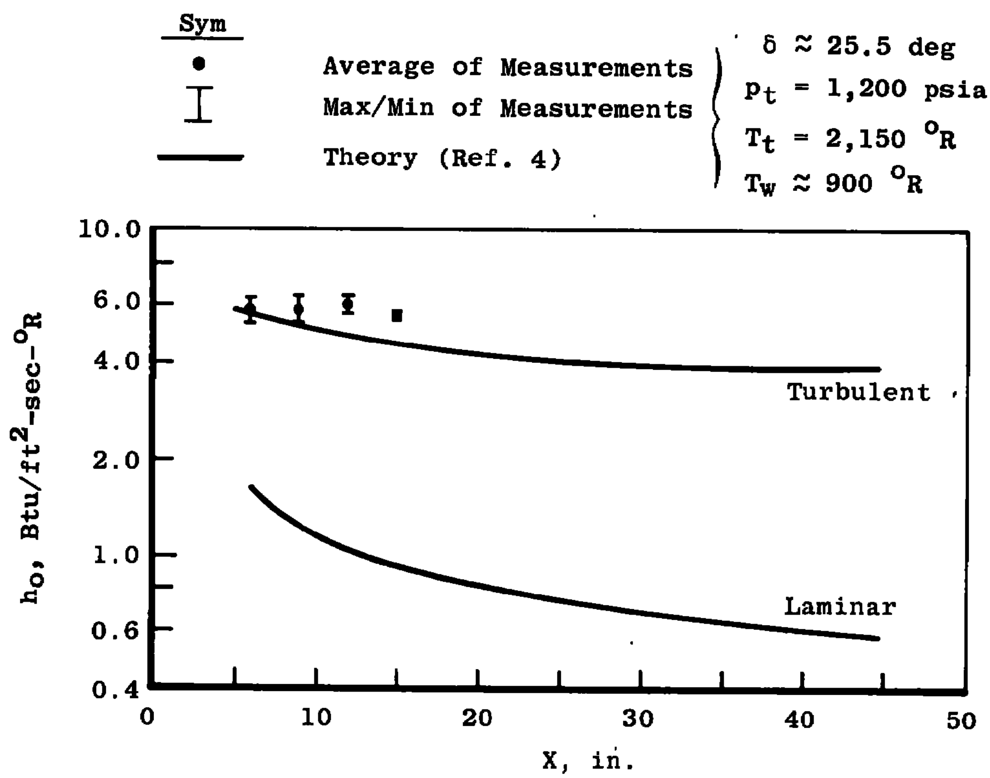
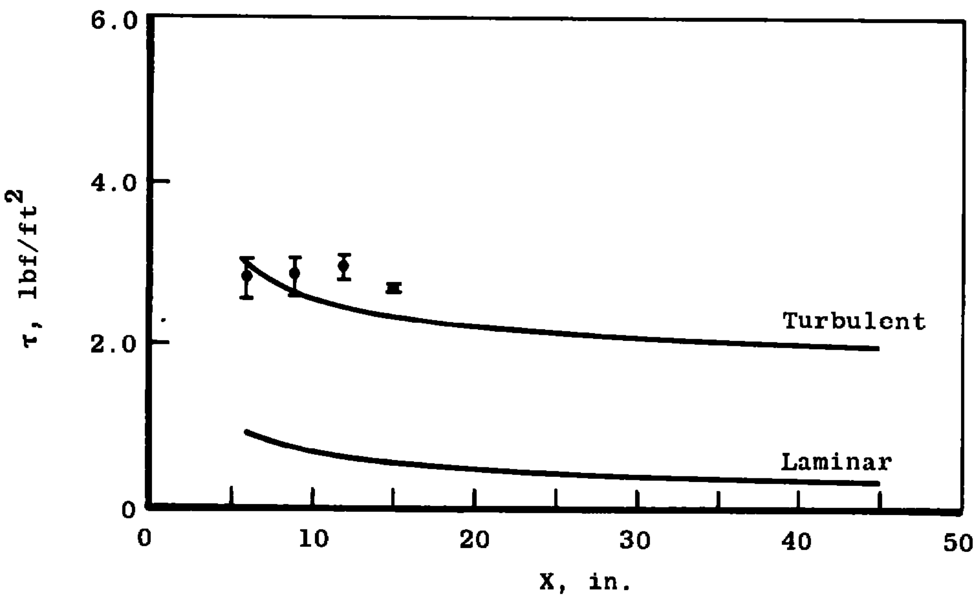


Figure 9. Flow-field shadowgraph of Sample 2, Run 23.



a. Heat-transfer distribution along centerline



b. Shear stress distribution along centerline

Figure 10. Heat-transfer and shear stress distributions on wedge surface.

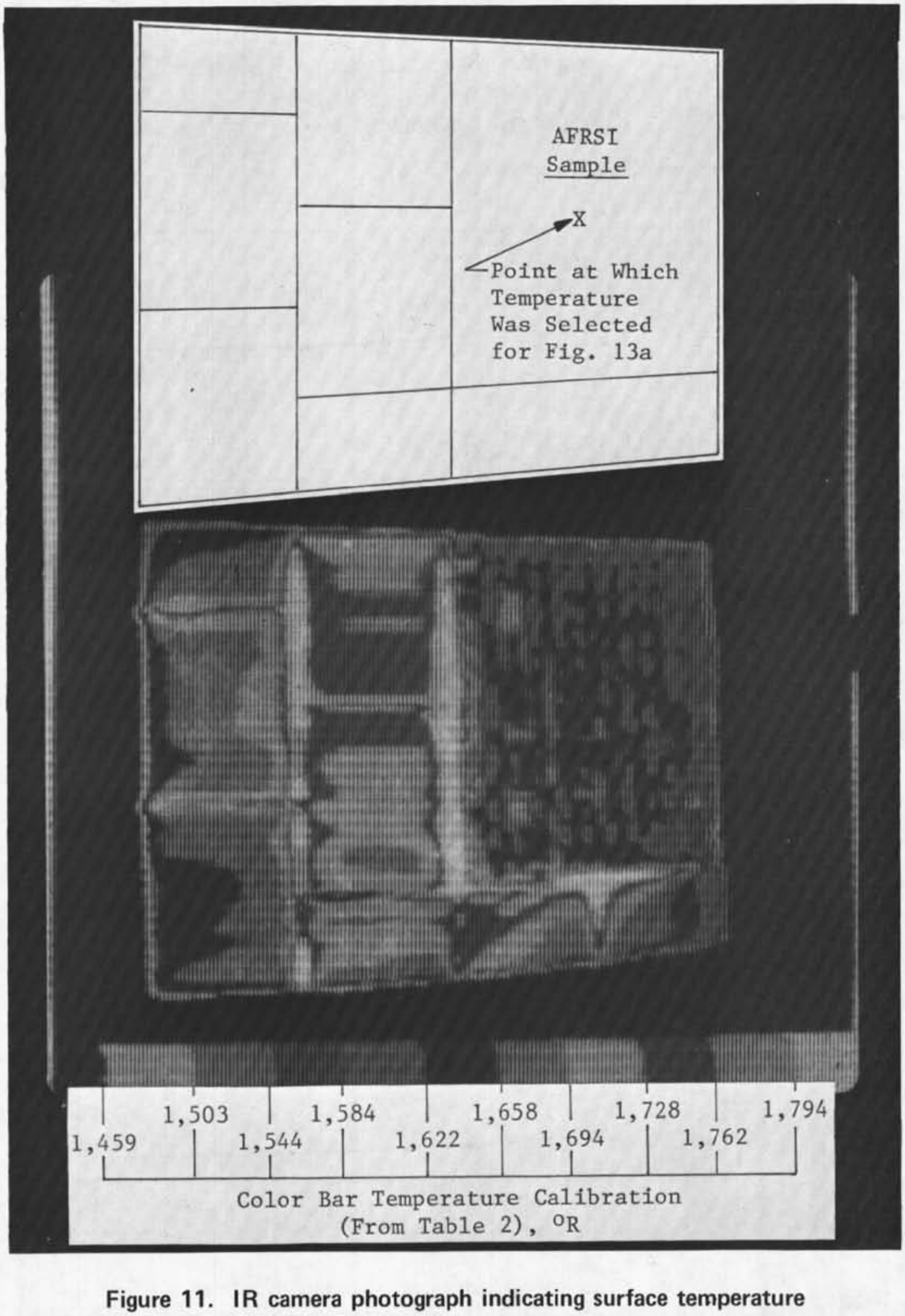
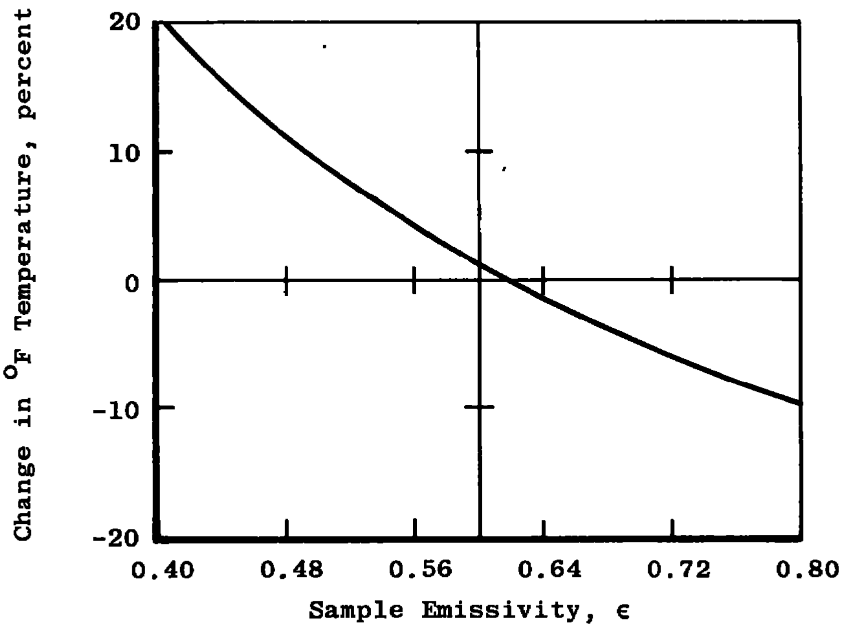
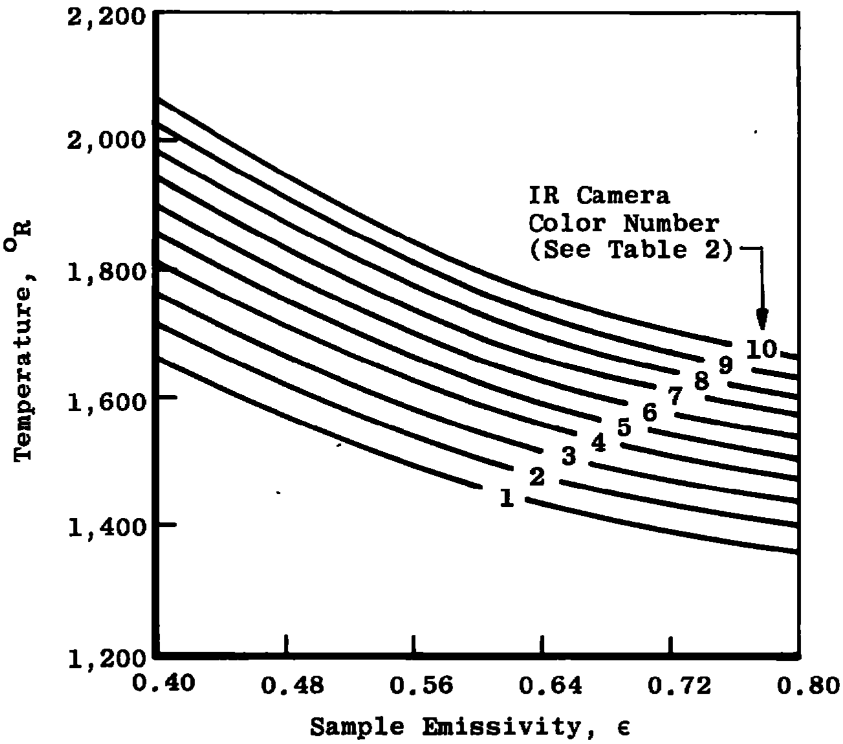


Figure 11. IR camera photograph indicating surface temperature of Sample 2, Run 23.

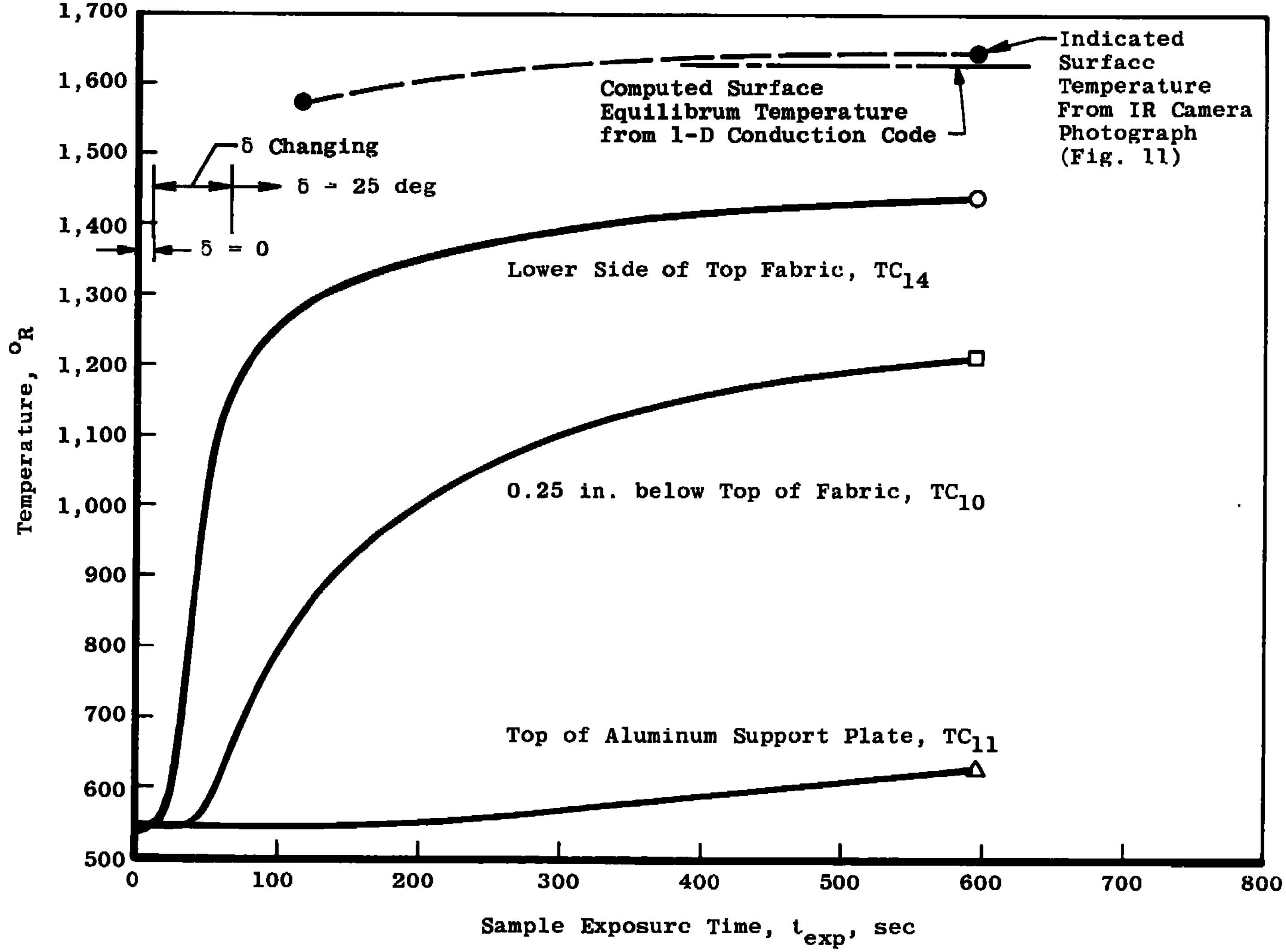


a. Percent change of IR camera temperature calibration with sample emissivity



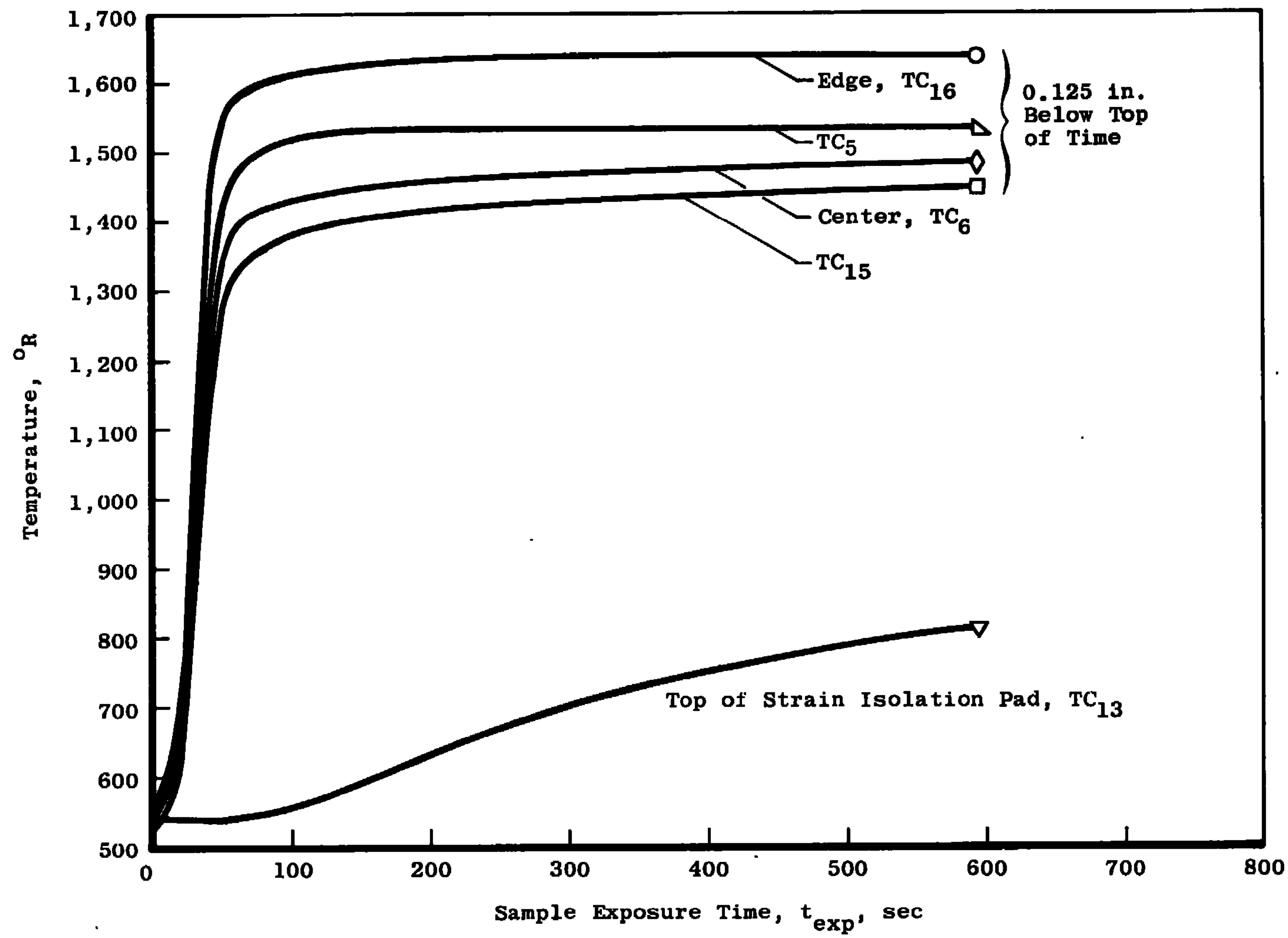
b. IR camera temperature calibration (Runs 2 through 29) with emissivity

Figure 12. Influence of sample emissivity on IR camera temperature calibration.

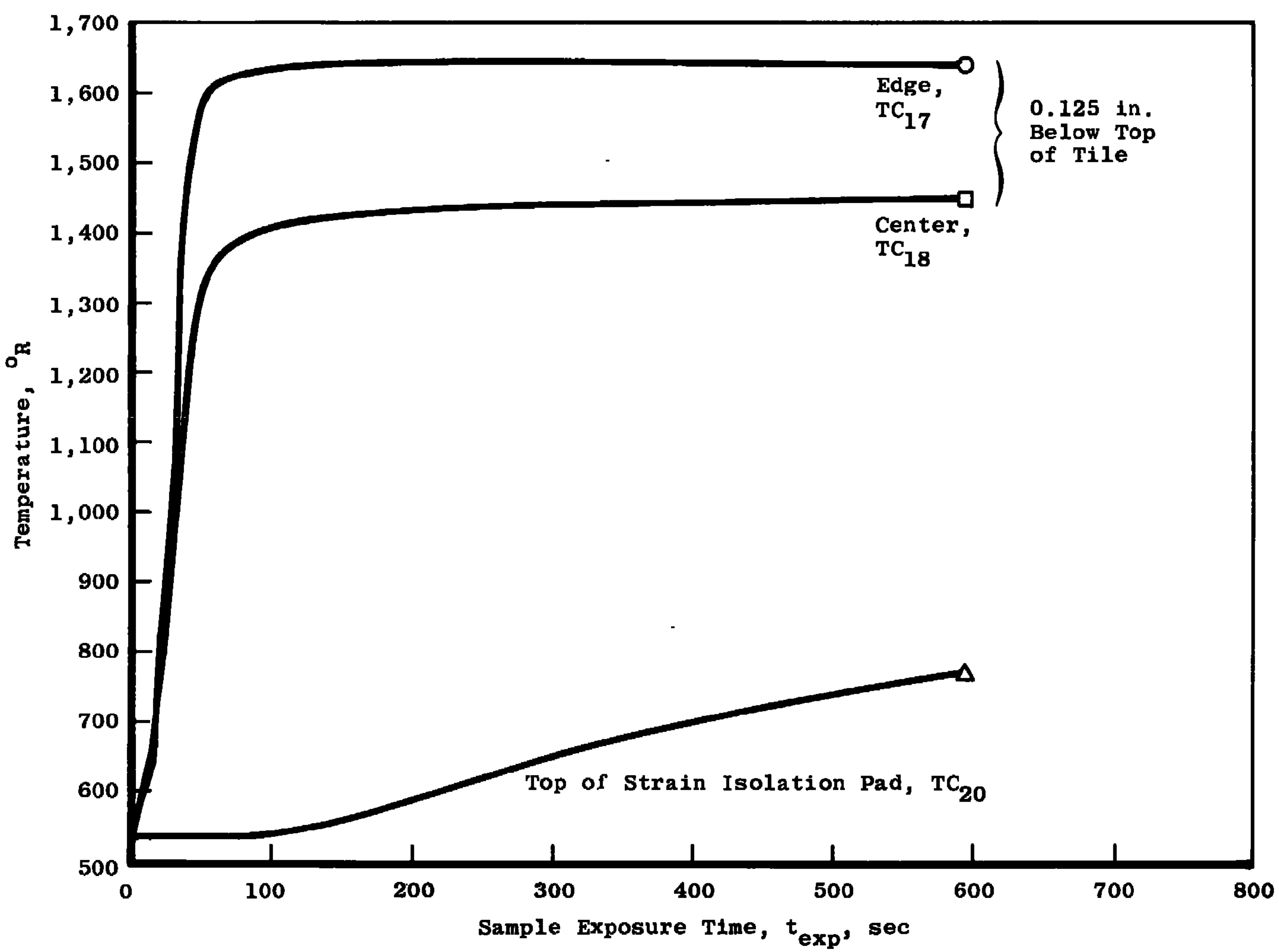


a. Temperature rise in AFRSI material

Figure 13. Temperature response of Sample 2 to test environment, Run 23.



b. Temperature rise in RSI tiles
Figure 13. Continued.



b. Concluded
Figure 13. Concluded.

Table 1. Test Summary

Sample Number	Sample Position,* deg	Run
1	0	2, 3, 4
2	0	9, 10, 11, 12, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29
3	180	1
4	0	5, 6, 7, 8, 13, 14, 15, 16, 17, 18

*Sample position locates the sample on the wedge. Looking downstream from the wedge front, the zero position places the AFRSI sample on the left side of the wedge, and the 180-deg sample position puts the AFRSI sample on the right side of the wedge.

Table 2. IR System Color/Temperature Calibration.

Color Number	Temperature at Color Lower Boundary, ^{o}R	
	Run 1	Runs 2 through 29
1	-	1,459
2	-	1,503
3	754	1,544
4	1,119	1,584
5	1,289	1,622
6	1,418	1,658
7	1,527	1,694
8	1,623	1,728
9	1,712	1,762
10	1,794	1,794

See Fig. 11 for color temperature calibration

APPENDIX A

SURFACE EQUILIBRIUM TEMPERATURE COMPUTATION

A one-dimensional conduction computer code (Ref. 5) was used to compute the fabric sample surface equilibrium temperature considering heat input to the fabric by aerodynamic convective heating and heat losses from the fabric surface to the tunnel walls by radiation. The sum of these heat-transfer mechanisms represents the amount of heat available to be conducted into the fabric sample. The equation for the heat available for input into the conduction code is as follows:

$$\dot{q} = h_o\left(T_t - T_w\right) - \sigma\epsilon\left(T_w^4 - T_R^4\right) \tag{A-1}$$

The measured heat-transfer coefficient, h_o, from Fig. 10a and the computed emissivity from Fig. 8 ($\epsilon = 0.62$) were used in the above equation; σ is the Stefan-Boltzmann constant, T_w is the sample surface temperature, and T_R is the reference (tunnel wall) temperature (530 to 70°F) for the radiation term.

The conduction code was begun by computing the heat input for the sample initial temperature of 540°R. The conduction code then computed the temperature rise in the fabric with this heat input for a specified time (6 sec in this case). At that time a new surface temperature was computed and used in Eq. (A-1) to compute a subsequent heat input. The process was continued for 600 sec, which was sufficient for the equilibrium condition ($\dot{q} = 0$) to be reached. Only the top layer of fabric was considered in this computation because the thermal contact between all subsequent layers was not defined. The backside of the fabric was assumed to be insulated. The physical properties of the top layer used in these calculations were as follows:

Density = 75 lbm/ft^3

Specific heat = 0.25 Btu/lbm-°R

Thermal conductivity = 8.75×10^{-6} Btu/ft-sec-°R

Thickness = 0.010 in.

The calculated equilibruim surface temperature was 1,630 °R.

NOMENCLATURE

E_R	Equivalent millivolt output of a platinum thermocouple at connector temperature (T_{R1} or T_{R2}), mv
E_{TC}	Total millivolt output of the platinum thermocouple, mv
ΔE	Millivolt output of gardon-type heat gages, mv
e_{b_λ}	Blackbody spectral emissivity at 530°R
h_o	Heat-transfer coefficient [see Eq. (5)], Btu/ft^2-sec-°R
M	Mach number
p	Static pressure, psia
p_t	Total pressure measured in tunnel stilling chamber, psia
$\dot{q}$	Measured heat flux or computed heat input to sample surface, Btu/ft^2-sec
Re	Unit Reynolds number, ft^{-1}
SF	Gardon-type heat gage scale factor, Btu/ft^2-sec/mv
T	Static temperature, °R
T_{aw}	Adiabatic wall temperature, °R
T_g	Heat gage measured temperature, °R
T_{R1}, T_{R2}	Measured reference temperature at connector, °R
T_t	Total temperature measured in tunnel stilling chamber, °R
TC_i	Output of thermocouple i, °R
Δt_{exp}	Exposure time, sec

V	Velocity, ft/sec
X	Distance from wedge leading edge (see Fig. 4b), in.
X_λ	IR camera spectral response factor
δ	Wedge angle with respect to free stream, deg
ϵ	Fabric sample total emissivity
ϵ_λ	Fabric sample spectral emissivity
λ	Wavelength, μ
μ	Mach angle, $\sin^{-1}(1/M)$, deg
σ	Stefan-Boltzmann constant, 4.761×10^{-13}, Btu/ft^2-sec-($^\circ$R)^4
τ	Computed shear stress [Eq. (7)], lbf/ft^2

SUBSCRIPTS

w	Wedge flow conditions

Note: Unsubscripted parameters denote tunnel free-stream conditions.